Lake Tahoe Total Maximum Daily Load

Technical Report

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List of Acronyms and Abbreviations

These acronyms and abbreviations appear in various chapters of the report. Most of these are initially spelled out individually in each chapter, but this list is provided for ease of reference.

AnnAGNPS	Agricultural Non-Point Source Pollutant Version 3.30
BAP	Biologically Available Phosphorus
BF	Baseflow
BME	Bradu-Mundlak Estimator
BMP	Best Management Practice
C	Carbon
°C	Degrees Celsius
CARB	California Air Resources Board
CDM	Camp Dresser and McKee
CDOM	Colored dissolved organic matter
CFR	Code of Federal Regulations
cfs	cubic feet per second
CICU	Commercial/Institutional/Communications/Utilities
CO	Carbon monoxide
CONCEPTS	Conservational Channel Evolution and Pollutant Transport System
CTC	California Tahoe Conservancy
CWA	Clean Water Act
DCNR	Nevada Department of Conservation and Natural Resources
DEM	Digital Elevation Model
DIN	Dissolved Inorganic Nitrogen
DLM	Dynamic Lake Model
DON	Dissolved Organic Nitrogen
DOP	Dissolved organic phosphorus
DOQs	Digital Orthophotographic Quadrangles
DRI	Desert Research Institute
DYRESM	Dynamic Reservoir Model
D-team	TMDL Development Team
EMC	Event Mean Concentration
EP	Erosion Potential
ET	Evapotranspiration
ft	Feet
GIS	Geographic Information System
GQUAL	Lake Tahoe Watershed General Water Quality Module
HIC	Hard Impervious Cover
HSPF	Hydrologic Simulation Program – FORTRAN
HYSEP	USGS hydrograph separation algorithms
I_B	Bank-stability index
IVZ	Intervening Zones
IWQMS	Integrated Water Quality Management Strategy

L	Liter
LA	Load Allocation
LC	Loading Capacity
LCM	Lake Clarity Model
LSPC	Loading Simulation Program in C++(Lake Tahoe Watershed Model)
LTADS	Lake Tahoe Atmospheric Deposition Study
LTBMU	Lake Tahoe Basin Management Unit
LTIMP	Lake Tahoe Interagency Monitoring Program
MOS	Margin of Safety
MVUE	Minimum Variance Unbiased Estimator
m	Meter
µm	Micrometer
mg	milligrams
mL	Milliliter
MFR	Multi-family Residential
MT	Metric Ton
NAC	Nevada Administrative Code
NADP	National Atmospheric Deposition Program
NCDS	National Climatic Data Center
NDEP	Nevada Division of Environmental Protection
NDOT	Nevada Department of Transportaiton
NHD	National Hydrography Dataset
NH_4^+	Ammonium
NO_x	Oxides of Nitrogen
NO_3^-	Nitrate
NRCS	National Resource Conservation Service
NTU	Nephelometric Turbidity Units
n/y	Number of Particles per Year
OM	Organic Matter
ONRW	Outstanding National Resource Water
PEVT	Potential Evapotranspiration
PM	Particulate Matter
PN	Particulate Organic Nitrogen
PO_4^{-3}	orthophosphate
PON	Particulate organic nitrogen
PP	Particulate Phosphorus
PPr	Primary Productivity
Q-wtd	Flow weighted
RGAs	Rapid Geomorphic Assessments
RMHQs	Requirements to Maintain Higher Quality
RO	storm-flow
ROG	Reactive organic gases
SAG	Source Analysis Group
s.d.	Standard deviation
SFR	Single-family Residential
SNOTEL	SNOwpack TELemetry

SNPLMA	Southern Nevada Public Lands Management Act
SRP	Soluble Reactive Phosphorus
SWE	Snow Water Equivalent
SWQIC	Storm Water Quality Improvement Committee
SWRCB	State Water Resources Control Board
S-XRF	Synchroton-X-Ray Fluorescence
TDP	Total Dissolved Phosphorus
TERC	Tahoe Environmental Research Center
THP	Total Acid-Hydrolyzable-Phosphorus
TKN	Total Kjeldahl Nitrogen (all organic nitrogen plus NH_4^+)
TKN + nitrate	Total Dissolved Nitrogen
TMDL	Total Maximum Daily Load
TN	Total Nitrogen
TON	Total Organic Nitrogen
TP	Total Phosphorus
TRG	Tahoe Research Group
TROA	Truckee River Operating Agreement
TRPA	Tahoe Regional Planning Agency
TSS	Total Suspended Sediment
UC Davis	University of California Davis
USACE	United States Army Corps of Engineers
USDA	United States Department of Agriculture
USEPA	United States Environmental Protection Agency
USFS	United States Forest Service
USGS	United States Geological Survey
VEC	Vertical Extinction Coefficient
WLA	Waste Load Allocation
WQS	Water Quality Standard
WVLL	Ward Valley Lake Level
XRF	X-ray Fluorescence

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Numerous projects were funded as part of the Lake Tahoe TMDL and were intended for direct use in this Technical Report. In some cases, the language from portions of those project reports was directly used in this document with minor editing. For areas where new information was not collected, the most recent and comprehensive analyses were used. In particular, the following reports were conducted in direct support of the Lake Tahoe TMDL and, at least portions of which are specifically incorporated into the text of this Technical Report.

Groundwater

USACE (United States Army Corps of Engineers). 2003. *Lake Tahoe Basin Framework Study: Groundwater Evaluation*. U.S. Army Corps of Engineers, Sacramento District.

Stream Channel

Simon, A., E.J. Langendoen, R.L. Bingner, R. Wells, A. Heins, N. Jokay and I. Jaramillo. 2003. *Lake Tahoe Basin Framework Implementation Study: Sediment Loadings and Channel Erosion*. USDA-ARS National Sedimentation Laboratory Research Report. No. 39.

Simon, A. 2006. *Estimates of Fine-Sediment Loadings to Lake Tahoe from Channel and Watershed Sources*. USDA-Agricultural Research Service, National Sedimentation Laboratory. Oxford, MS.

Atmospheric

CARB (California Air Resources Board). 2006. *Lake Tahoe Atmospheric Deposition Study (LTADS)*. Final Report – August 2006. Atmospheric Processes Research Section, California EPA, Sacramento, CA.

Upland
Tetra Tech, Inc. 2007. *Watershed Hydrologic Modeling and Sediment and Nutrient Loading Estimation for the Lake Tahoe Total Maximum Daily Load*. Final modeling report. Prepared for the Lahontan RWQCB and University of California, Davis.

Shoreline Erosion
Adams, K.D. and T.B. Minor. 2001. *Historic Shoreline Change at Lake Tahoe from 1938 to 1998: Implications for Water Clarity.* Desert Research Institute, Reno, NV. Prepared for the Tahoe Regional Planning Agency.

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Lake Clarity Modeling
Sahoo, G.B., S.G. Schladow and J.E. Reuter. 2006. Technical support document for the Lake Tahoe Clarity Model. Tahoe Environmental Research Center, John Muir Institute of the Environment, University of California, Davis. 56 p.

Sahoo, G.B., S.G. Schladow and J.E. Reuter. 2007. *Linkage of Pollutant Loading to In-lake Effects.* University of California, Davis – Tahoe Environmental Research Center. Prepared for the Lahontan RWQCB.

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1 Introduction

This report focuses on the evaluation of pollutant sources and the amount of pollutant load reduction that needs to occur, to achieve water quality objectives protecting the optical properties of water in Lake Tahoe. This is the first step towards completion of Final Lake Tahoe Total Maximum Daily Load (TMDL) for fine sediment, nitrogen and phosphorus which are the pollutants responsible for the continued loss of deep water transparency in Lake Tahoe.

> **Clarity vs. Transparency**
>
> While annual Secchi disk measurements are commonly referred to as clarity, this measurement is actually defined as transparency in regulatory documents. Clarity is defined as vertical extinction of light in regulatory documents. Collectively, these measurements are referred to as optical properties in this report.

The information contained in this report is intended to provide the framework for the evaluation of various pollutant control opportunities during the development of an Integrated Water Quality Management Strategy (IWQMS). This strategy will articulate how the restoration of lake transparency will be accomplished. The development of the IWQMS involved extensive public participation for input regarding the potential opportunities for implementation of pollutant control measures. Ultimately through the IWQMS process, pollutant load reduction allocations were developed along with implementation and monitoring plans that are part of the Final Lake Tahoe TMDL.

A TMDL is a written, quantitative assessment of water quality problems and contributing pollutant sources. It identifies one or more numeric targets based upon existing water quality standards and specifies the maximum amount of pollutant a waterbody can receive while remaining in attainment of water quality objectives. The goal of the TMDL, when implemented, is that the waterbody fully attain its designated beneficial uses by meeting existing water quality objectives. Consequently, a completed TMDL provides the scientific basis and framework for a comprehensive water quality restoration plan.

The Lake Tahoe TMDL is being developed cooperatively between the States of California and Nevada and is intended to meet the planning and regulatory needs of both states. It is also anticipated that the Final Lake Tahoe TMDL will meet the planning requirements of the United States Environmental Protection Agency (USEPA) and the Tahoe Regional Planning Agency (TRPA). The organization and implementation of this multi-agency effort is being coordinated through a process called Pathway in the Lake Tahoe basin for the Lahontan Water Board, Nevada Divison of Environmental Protection, Tahoe Regional Planning Agency, and the United States Forest Service, Lake Tahoe Basin Management Unit. The Pathway planning process was initiated to update and make consistent all the various resource management documentation covering the Lake Tahoe basin. Additional information on the Pathway process can be obtained from the Pathway2007.org website.

The Federal Clean Water Act (CWA) requires the development of TMDLs for the protection of beneficial uses and attainment of established water quality objectives for impaired waterbodies as designated under Section 303(d) list of the CWA. Lake Tahoe has been identified as not meeting established water quality objectives intended to protect its famed water clarity and transparency. When finalized, the Lake Tahoe TMDL will provide a comprehensive quantitative evaluation of (1) major pollutant loading sources, (2) effect of these pollutants on Lake Tahoe's transparency, (3) degree of pollutant load reduction needed and (4) how load reductions can be achieved.

TMDLs are generally limited to the evaluation of a single pollutant-waterbody combination. However, the declining transparency of Lake Tahoe is the result of a complex interaction of different pollutants originating from diverse sources. The Lake Tahoe TMDL specifically addresses the three pollutants responsible for transparency reduction (fine sediment particles, nitrogen, and phosphorus), as it is the interaction of these pollutants that are responsible for the impairment of the Lake Tahoe's transparency. Because of this complex interaction, it was necessary to evaluate the three pollutants simultaneously.

Research and information collection in support of this document was initiated in 2001 and this report is the culmination of several years of effort to initiate, develop and synthesize new and historical information regarding the impairment of Lake Tahoe's transparency. This effort included contributions from numerous state, federal, academic and private entities that involved the participation of over 100 contributing scientists. Significant combined funding from state and federal agencies has allowed the most comprehensive and thorough evaluation of pollutant sources and lake effect ever completed in the Tahoe basin.

1.1 Overview of TMDL Program

This section provides background on the Federal TMDL Program and how these requirements are being fulfilled by the Lake Tahoe TMDL Program. This section includes a discussion of federal water quality requirements that provide the framework for protecting and restoring the nation's waters. Central to this framework is the Federal Clean Water Act which provides the regulatory authority for the development of TMDLs.

1.1.1 Federal Water Quality Requirements

The United States Congress enacted landmark legislation in 1972. This statute, the Federal Water Pollution Control Act, referred to as the Clean Water Act of 1972 (CWA), expanded and built upon existing laws. The goal of the CWA is to restore and maintain the chemical, physical and biological integrity of the nation's waters. Thus, the CWA established a regulatory framework for protecting and restoring surface waterbodies to conditions that attain existing water quality standards. The framework begins with adoption by states (subject to USEPA approval) of appropriate numeric or narrative water quality standards for the subject waterbody. The CWA defines "water quality standards" to include: (1) beneficial uses, (2) water quality criteria (i.e. water quality objectives) and (3) application of an antidegradation objective (i.e. nondegradation objective).

Beneficial uses identify appropriate uses of that water that are to be achieved and protected. The primary beneficial use relevant to this TMDL is non-contact water recreation, which protects the aesthetic enjoyment of Lake Tahoe's historical clarity, in both the pelagic (deep) and littoral (nearshore and shallow) zones of the lake.

Water quality criteria (or objectives) are limits on a particular pollutant or on a condition of a waterbody designated to protect and support the identified beneficial uses. These criteria can be expressed either as numeric or narrative criteria. When criteria are met, water quality is sufficient for the protection of identified beneficial uses. The deep water transparency standard for Lake Tahoe is not being met, therefore, Lake Tahoe is impaired by nitrogen, phosphorus, and fine sediment.

As mentioned above, an antidegradation policy is one of the minimum elements required to be included in a state's water quality standards. The antidegradation policy does not strictly prohibit degradation of water quality, except in a very limited circumstance. The antidegradation policy can be expressed as one of three tiers.

A Tier One policy states that any existing use and the water quality necessary to protect that use, must be maintained and protected. This means that whatever the existing use of the waterbody is, you are not allowed to make it worse. If water quality needs to be improved to meet the standards then control programs must be put into place to meet the water quality standard. This can be considered the most basic level of water quality protection under the CWA.

Tier Two antidegradation, or maintenance of high-quality water, says that if water quality is better than needed to protect beneficial uses, the water quality can be allowed to deteriorate to a level that still maintains the beneficial use. However, it is up to the state to make the decision whether or not to allow the degradation. In all cases, the state is required to involve the public, and other federal agencies, as necessary. The decision to allow deterioration in water quality is based on the finding that a lower water quality is necessary to support important economic and social development in the area in which the water is located.

Tier Three affords the highest level of protection under the CWA with the designation of Outstanding National Resource Water (ONRW). This is a classification created by the USEPA which does not allow any degradation if the state classifies a waterbody as an ONRW. This designation is usually reserved for exceptional waters with unique ecological and/or social significance needing special protection. Temporary water quality degradation is allowed in an ONRW only if "temporary" is defined in terms of weeks and months, and not years. Lake Tahoe has been designated an ONRW by the State of California since 1980.

1.2 National TMDL Program

Section 303(d) of the CWA and the USEPA Water Quality Planning and Management Regulations (Title 40 of the *Code of Federal Regulations* [CFR] Part 130) require states to: 1) identify impaired waters where required pollution controls are not stringent enough to attain water quality standards and 2) establish TMDLs for such waters for the pollutants that are contributing to the water quality impairments even if pollutant sources have implemented technology-based controls.

The impaired waters requiring the development of TMDLs are included on the states' Section 303(d) lists, which are submitted to USEPA every two years for approval. A TMDL establishes the maximum allowable load (mass per unit of time) of a pollutant that a waterbody is able to assimilate and still support its designated uses. The maximum allowable load is determined on the basis of the relationship between pollutant sources and the water quality of the specific water body. A TMDL provides the scientific basis for a state to establish water quality-based controls to reduce pollution from both point and nonpoint sources to restore and maintain the quality of the states' water resources (USEPA 1991). Point sources of pollutants are discrete, conveyed pollutant sources such as stormwater, while non-point sources of pollutants are diffuse pollutant sources such as atmospheric deposition.

Furthermore, TMDLs provide a means to integrate the management of both point and nonpoint sources of pollution through the establishment of wasteload allocations (WLAs) for point source discharges, and load allocations (LAs) for nonpoint sources. TMDLs are to be established at levels necessary to attain and maintain applicable narrative and numeric water quality standards with consideration given to seasonal variations and a margin of safety (MOS). The goal of the TMDL, when implemented, is that the waterbody fully attain its designated beneficial uses and water quality objectives.

The general equation describing the TMDL, the allocation and margin of safety components is as follows (USEPA 1991):

$$\mathrm{TMDL} = \mathrm{LC} = \sum \mathrm{WLA} + \sum \mathrm{LA} + \mathrm{MOS} \qquad \textbf{Equation 1}$$

Where:
- $\sum$ = sum of
- LC = loading capacity, or the greatest loading a waterbody can receive without exceeding water quality standards;
- WLA = wasteload allocation, or the portion of the TMDL allocated to existing or future point sources;
- LA = load allocations, or the portion of the TMDL allocated to existing or future nonpoint sources and natural background;
- MOS = margin of safety, or an accounting of uncertainty about the relationship between pollutant loads and receiving water quality.

The margin of safety can be provided implicitly through conservative analytical assumptions or explicitly by reserving a portion of loading capacity. In addition to the above equation, the federal TMDL program requires that certain elements be included in a TMDL evaluation. The required elements and a brief explanation of each are provided in Table 1-1.

Table 1-1. Required TMDL elements.

Required Element	Definition
Problem Statement	The problem statement describes the impairment of the identified waterbody in terms of which currently designated beneficial use is not being attained. In other words, the Problem Statement explains which standards are being exceeded in that lake, stream or river. In the case of Lake Tahoe, it is the non-attainment of the established clarity objectives that has caused the lake to be listed for not meeting the non-contact beneficial use, or 'aesthetic standard'.
Numeric Targets	A Numeric Target needs to be established for each TMDL in order to quantify pollutant load reductions necessary to support beneficial uses designated for that waterbody. In some instances the Numeric Target needs to be determined based upon the evaluation of a narrative standard that does not specifically determine a numeric goal for the protection of beneficial uses. In the case of Lake Tahoe, a specific numeric standard for clarity currently exists.
Source Assessment	This element of TMDL development is intended to identify the location, type, frequency and magnitude of all known loading sources (both point and nonpoint). The principle product of the Source Assessment is the development of an accurate estimate, or budget, of the total pollutant load currently entering a waterbody.
Linkage Analysis	The Linkage Analysis is performed to understand what effect the identified pollutant sources and their respective loads are having on the identified waterbody. Once this is performed, a determination of the waterbody's assimilative capacity is identified. The assimilative capacity is the estimation of the maximum amount of pollutant a water body can assimilate without exceeding the existing water quality objectives. The linkage analysis is then able to quantify future pollutant loading levels that will be necessary to achieve the numeric targets identified in the target analysis.
Load Allocations	The assimilative capacity defines the amount of pollutant load reduction needed to achieve applicable water quality standards. Once the overall load reduction has been estimated, it then needs to be distributed or "allocated" among the significant sources of the pollutant identified in the source analysis. The determination and development of load allocations will be completed as part of the Integrated Water Quality Management Strategy (IWQMS). The development of the IWQMS is part of Phase Two of TMDL development. Consequently Load Allocations have not been developed for this report.
Margin of Safety	A Margin of Safety (MOS) must be included in the analysis to account for uncertainties in (a) the relationship between effluent limitations and the water quality of the receiving water and (b) the estimation of existing pollutant sources. The MOS may be provided implicitly through the use of conservative analytical assumptions or explicitly as an unallocated portion of the allowable loading. The MOS must also consider and provide an allocation for the potential loading resulting from the impacts associated with future growth. The MOS will be part of the Final TMDL and is not included in this document.
Monitoring and Review Plan and Schedule of Revision	The TMDL monitoring plan will track source load reductions, indicators and milestones over time, accounting for variability and including regular progress reports to inform decision-makers on the need for TMDL and/or Implementation Plan revision. This is to be developed for Lake Tahoe through the Pathway process and is not included in this report.
Implementation Plan (Required in California only)	Although not currently required by USEPA guidance, TMDLs adopted by the state of California must include an Implementation Plan. The Implementation Plan will present a detailed process for achieving load reductions beginning with current loads and resulting in the TMDL over an agreed-upon timeframe. Milestones will include interim load reductions at specified, regular intervals. This effort is currently being completed through the Pathway process and is not included in this report.

1.3 Lake Tahoe TMDL Program

Lake Tahoe's exceptional characteristics combined with its unique resource management/regulatory setting, presented particular challenges and opportunities that are illustrated in this section. The multi-agency approach taken to develop the Tahoe TMDL Program provided a vast range of expertise that was particularly valuable given the scheduling needs required for inclusion within the Pathway process. This section describes the scope of the Lake Tahoe TMDL, the phases of TMDL development for Lake Tahoe and the research program developed to support the Lake Tahoe TMDL.

1.3.1 Scope of Lake Tahoe TMDL Program

The Section 303(d) listing of Lake Tahoe identifies the lake as impaired for not attaining applicable water quality objectives. Specifically, the Lake Tahoe TMDL is being developed by California and Nevada to address pollutant loading from all sources to achieve existing water quality objectives for deep water clarity and transparency. This TMDL only addresses the pollutants impacting deep water transparency in Lake Tahoe, namely the loading of nitrogen, phosphorous and fine sediment.

The Lake Tahoe TMDL addresses only the pelagic (deep water) waters of Lake Tahoe and does not address the nearshore waters. The nearshore is defined as the area of the lake that is close to shoreline where the bottom of the lake is visible (LRWQCB 1995). The pelagic area of the lake is where the bottom is no longer visible from the surface. This TMDL report summarizes data from studies in the nearshore but does not address the water quality objectives for the nearshore. Though additional research is needed to better understand the relationship between upland activities and effects in the nearshore, this TMDL assumes that efforts to prevent pollutants from entering surface discharge for the protection of pelagic lake clarity should also benefit conditions in the nearshore. An exception to this may be isolated "hot spots" (i.e. marinas) in the nearshore area. These areas should be identified and addressed as needed as part of ongoing restoration efforts.

1.3.2 Phases of TMDL Development

For planning purposes, the development of the Lake Tahoe TMDL has been divided into three distinct phases. Phase One involved the research to develop loading estimates from major sources and estimate the amount of pollutant load reduction needed to attain applicable standards. The results of that evaluation are contained in this Technical Report. Phase Two of TMDL development includes a public process to determine the required load reduction allocations and to develop an implementation plan that outlines how pollutant load reductions will be achieved. The work to complete Phase Two is collectively referred to as the Integrated Water Quality Management Strategy (IWQMS). Once completed in 2008, the IWQMS formed the framework for water quality restoration planning and updating of regulatory documents through the Pathway process. The Pathway process also developed an adaptive management framework for the Tahoe basin and is expected to be the cornerstone of Phase Three of the TMDL process which identified the need for continuous updating and evaluation of TMDL loading estimates and models. The products of each phase are summarized in Table 1-2 and are discussed in greater detail below.

Table 1-2. TMDL Phased Development.

TMDL phase	Questions	Products
Phase One — Pollutant Capacity and Existing Inputs	**What pollutants are causing Lake Tahoe's clarity loss?**	Research and analysis of fine sediment, nutrients and meteorology
	How much of each pollutant is reaching Lake Tahoe?	Existing pollutant input to Lake Tahoe from major sources
	How much of each pollutant can Lake Tahoe accept and still achieve the clarity goal?	Linkage analysis and determination of needed pollutant reduction
		Document: TMDL Technical Report
Phase Two — Pollutant Reduction Analysis and Planning	**What are the options for reducing pollutant inputs to Lake Tahoe?**	Estimates of potential pollutant input reduction opportunities **Document:** Pollutant Reduction Opportunity Report
	What strategy should we implement to reduce pollutant inputs to Lake Tahoe?	Integrated strategies to control pollutants from all sources **Document:** Integrated Water Quality Management Strategy Project Report
		Pollutant reduction allocations and implementation milestones
		Implementation and Monitoring Plans
		Document: Final TMDL
Phase Three — Implementation and Operation	**Are the expected reductions of each pollutant to Lake Tahoe being achieved?**	Implemented projects & tracked pollutant reductions
	Is the clarity of Lake Tahoe improving in response to actions to reduce pollutants?	Project effectiveness and environmental status monitoring
	Can innovation and new information improve our strategy to reduce pollutants?	TMDL continual improvement and adaptive management system, targeted research
		Document: Periodic Milestone Reports

Phase One

The first phase of TMDL development initiated a significant research effort. In July of 2001, a budget request made by the Governor of California was approved by the State Legislature and provided funding for an ambitious 5-year program to investigate pollutant sources and the magnitude of load reductions needed to restore lake clarity. This initial round of funding provided to the Water Board and the California Air Resources Board (CARB) initiated significant research efforts to fill information gaps and develop the tools needed to perform a basin-wide evaluation of pollutant sources and their affect on Lake Tahoe.

To compliment this initial research effort and secure funding to complete Phase Two of the TMDL, the project team wrote numerous funding proposals that resulted in significant additional funding contributions from the federal government and both states. This partnership is nationally significant, reflecting both on the importance of Lake Tahoe as a resource and the dedication of state, regional and federal agencies to better understand and protect Lake Tahoe.

The research objectives of Phase One of TMDL development were to:

- Identify the significant sources of pollutants impacting the transparency and clarity of Lake Tahoe,
- Provide quantitative estimates of pollutant loading from the identified sources,
- Provide a linkage between those pollutants and response by optical properties within the lake,
- Provide quantitative estimates of the load reductions needed to achieve applicable water quality objectives protecting the optical properties of Lake Tahoe, and
- Summarize the results of the research and applied science used to achieve these objectives in a Technical Report.

Descriptions and summaries of the research and applied science used to achieve these objectives are contained in this report. This information is intended to assist in development of scientifically informed decisions needed as part of Pathway, IWQMS and development of the Final Lake Tahoe TMDL.

Phase Two

The second phase of TMDL development facilitated agency and stakeholder discussion on load reduction opportunities. This phase of TMDL development explored various pollutant control opportunities, packaged these opportunities into integrated implememation strategies, and developed a single Recommended Strategy for TMDL implemenation. The development of this strategy is the cornerstone of the Phase Two effort and provides a solid planning platform for the management of water quality and the restoration of Lake Tahoe's clarity and transparency. Phase Two also developed the remaining elements for the Final TMDL, including Recommended Strategy details, source-specific pollutant load allocations, waste load allocations for NPDES-permitted urban jurisdictions, along with implementation and monitoring plans to achieve water quality objectives.

Phase Three

The continuous incorporation of future research efforts, monitoring data and improved understanding is a fundamental intention of the Lake Tahoe TMDL Program. The estimates developed for this report provide a comprehensive evaluation of all pollutant sources and their effect on lake clarity. Many factors can affect these estimates including, data form and availability, quality of information, variability of complex ecosystems, unavoidable need for assumptions, and certainty of estimates all have the potential to impact the estimates developed. The project team minimized these effects as much as possible by drawing on the wealth of scientific information and expertise available in the Tahoe basin, but the need for continuous re-evaluation, interpretation and improvement was recognized early in the process. Phase Three of the Lake Tahoe TMDL will specifically address these needs by completing several tasks:

- Develop an adaptive management system to integrate new information, research and understandings,
- Provide a framework for the modification and tracking of pollutant load estimates and pollutant load reduction allocations over time,
- Identify additional research and information to improve quantified estimates,
- Explore opportunities for greater integration between pollutant source categories, agencies, funding, monitoring and direct application of future efforts.

The scientific framework developed by the TMDL program will allow for timely application of new information as well as the ability to evaluate the potential outcome of management actions in the future. This will allow for an increased ability to incorporate new information, evaluate potential implications of change, and estimate lake response in a much more timely and efficient manner.

1.3.3 TMDL Associated Research

Given its national significance, Lake Tahoe and its watershed have benefited from decades of research and scientific attention. Consequently, Lake Tahoe is a well-studied ecosystem with a rich database for TMDL application. Literally, hundreds of peer reviewed journal papers, and reports have been written on many aspects of Lake Tahoe and its watershed since studies first began over 40 years ago (Reuter and Miller 2000). Much of this information was used to address a series of questions associated with three critical issues relevant to the Lake Tahoe TMDL:

1) Identify major pollutant sources and where possible, quantify loading of nutrients and fine sediments to Lake Tahoe,
2) Determine the extent, to which the load of fine sediment and nutrients from the watershed and air basin can be effectively reduced by management and/or restoration activities,
3) Understand how Lake Tahoe's clarity will respond to environmental improvement and pollutant control efforts.

Many of the researchers who have studied Lake Tahoe and its environment for the past 10-20 years (and longer) are still very active in the scientific community. This has allowed TMDL researchers the ability to establish inter-disciplinary and inter-institutional science teams. Another key benefit to the rich database is that the many models that have been used in the Lake Tahoe TMDL effort were able to incorporate rate coefficients and other parameters which are developed with site specific data rather than depending on literature data. Moreover, the extensive monitoring data from the

Lake Tahoe Interagency Monitoring Program provides key intra- and inter-annual time series data sets for model population, calibration and validation.

Initiated in 2001, research associated with the development of the Lake Tahoe TMDL was specifically intended to build on the wealth of information available in the Tahoe basin. Key Management Questions relevant to the Lake Tahoe TMDL where evaluated and information gaps were identified that required additional evaluation for application in TMDL development. The development of these information needs was based on many events/efforts, including but not limited to: guidance from previous and ongoing research; Presidential Forum at Lake Tahoe in 1997; Lake Tahoe Watershed Assessment; Lake Tahoe Science Symposia; establishment of the Lake Tahoe Science Consortium; and the Pathway process.

Dr. John Reuter from the UC Davis Tahoe Environmental Research Center (UC Davis - TERC) was contracted as Research and Science Coordinator for the Lake Tahoe TMDL Program. Dr. Reuter developed, in coordination with the project team, a Science Plan for the Lake Tahoe TMDL that identified information gaps and tools needed for TMDL development. This plan greatly benefited from rich literature on Lake Tahoe, its watersheds, and its air basin. Significant contributions were provided from multiple academic, state, federal, and private consulting entities to complete the research and applied science contained in this report. The use of sound science continues into Phase Two and will be continuously improved thru Phase Three.

The following section provides brief descriptions of the research and applied science projects completed as part of the TMDL. This overview also includes some research projects completed since 2001 that directly applied to the TMDL. The collection and application of this information has provided a framework for the integration of science and information and its translation into management application through the TMDL program.

Sources of scientific information used to address these TMDL issues include:

- Historic Tahoe data and analyses
- Scientific literature
- New and existing monitoring data
- Laboratory experiments
- Field experiments
- Demonstration projects
- Statistical analyses
- Modeling – with calibration and validation
- Best professional judgment

Brief descriptions, by category, of the major, new TMDL science projects that were done in support of Phase One of the Lake Tahoe TMDL are provided below:

Watershed Model – In direct support of the TMDL, Tetra Tech has developed the Lake Tahoe Watershed Model using the Loading Simulation Program in C++ (LSPC). The watershed modeling system includes algorithms for simulating hydrology, sediment and water quality from over twenty land-use types in 184 subwatersheds. This model was used to estimate the current pollutant loading to the lake from surface runoff and will be used for the exploration of various scenarios during development of the IWQMS. An independent study was also conducted to determine the statistical relationship between land-use characteristics and loading.

Lake Clarity Model – The University of California, Davis (UC Davis), has been developing the Lake Tahoe Clarity Model (Lake Clarity Model) for several years based on the extensive data collected on lake processes by the Tahoe Environmental Research Center (TERC) (formerly Tahoe Research Group) and others over the last forty years. The Lake Clarity Model is a unique combination of sub-models including a hydrodynamic model, an ecological model, a water quality model and an optical model. This model was developed to specifically identify Lake Tahoe's response to pollutant loading and the pollutant reductions necessary for the protection of lake clarity.

Atmospheric Transport and Deposition – The California Air Resources Board (CARB) recently completed a large and significant effort to better characterize atmospheric pollutant sources, transport and deposition (*Lake Tahoe Atmospheric Deposition Study* – LTADS). This two year monitoring and modeling effort has provided updated and new information on the amount of nutrients and particulate matter generated in the basin (and out-of-basin) and the amount of deposition onto the lake surface resulting from these processes. LTADS, for the first time, quantified the deposition of particulate matter onto Lake Tahoe. Current and previous studies by the UC Davis-TERC, UC Davis DELTA Group, and the Desert Research Institute (DRI) were also used in quantifying atmospheric deposition.

Groundwater Loading – On the basis of currently available nutrient data from existing wells, an assessment of likely inflow and nutrient loading from five regions comprising the entire shoreline of Lake Tahoe was completed by the US Army Corps of Engineers.

BMP Feasibility Report – Using both national and local data, Geosyntech Consultants, evaluated the performance of urban runoff BMPs, and for the first time took a basin-wide approach to evaluating BMP performance.

Stream Channel Erosion – The U.S. Department of Agriculture's (USDA's) National Sedimentation Laboratory evaluated the significance of stream channel erosion as a source of fine sediment. This project quantified the significance of stream channel erosion relative to other major sources. This increased understanding will enable stream channel erosion to be treated as a discrete source of pollution in the Lake Tahoe TMDL.

Urban Stormwater Monitoring – Sixteen auto-samplers were deployed throughout the basin as part of the TMDL-funded Stormwater Monitoring Program in 2003 and 2004. These stations plus three stations already in operation were used to measure water quality in runoff from different urban land-uses. All storm events were measured for two consecutive years to better inform watershed modeling estimates of loading from different land-uses. This work was completed collaboratively between the DRI and UC Davis - TERC. This was the first time a comprehensive effort has been made at Lake Tahoe to characterize and quantify urban stormwater quality based on land-use. California Department of Transportation and Nevada Department of Transportation also conducted companion studies during the period 2001-2004 to determine the water quality of runoff from primary roads.

Biologically Available Phosphorus (BAP) – Measurements of ortho-phosphorus and total phosphorus underestimate and overestimate the phosphorus available for algal growth, respectively. However, monitoring programs rarely measure BAP. In a study conducted at the University of Nevada-Reno, researchers measured BAP from various sources in the Tahoe basin. This information was used in the Lake Clarity Model to estimate nutrients from stream channel erosion.

Nearshore Clarity – The DRI measured nearshore turbidity values through whole lake transects and focused study along the south shore. Real time measurements of turbidity where taken during different weather conditions to measure differences in nearshore turbidity. These studies indicate that nearshore turbidity is negatively impacted during surface flow events associated with snowmelt and rainfall runoff in urban areas.

Sources and Fate of Fine Particles – The importance of fine particles to Lake Tahoe's clarity only was first recognized in 1999 (Jassby et al. 1999). A series of in-lake investigations commenced in 1999 that have help characterize particle distribution and dynamics in Lake Tahoe. As part of the TMDL science program additional research and monitoring was done to investigate particle loading from the channelized tributaries. Additional investigations were also made to better understand the processes of particle aggregation, settling and ultimate removal from the water column.

Lake Tahoe Interagency Monitoring Program (LTIMP) - LTIMP is a cooperative program including both state and federal partners and is operationally managed by the U.S. Geological Survey (USGS), UC Davis - TERC, and the Tahoe Regional Planning Agency (TRPA). It was formed in 1979 (Leonard and Goldman 1981) and one of its main missions is to monitor flow, nutrient load and sediment loads from representative streams that flow into Lake Tahoe. The following streams are currently monitored and have been monitored since 1988: Trout Creek, Upper Truckee River, General Creek, Blackwood Creek, Ward Creek, Third Creek, Incline Creek, Glenbrook Creek, Logan House Creek and Edgewood Creek (Rowe et al. 2002). Because of variation in watershed characteristics around the basin and significant 'rain shadow' effects along the west-to-east direction across the lake, no single location is representative of all watersheds. Cumulative flow from these monitored streams comprises about 50 percent of the total discharge from all tributaries. Each stream is monitored on 30-40 dates each year and sampling is largely based on hydrologic events. Nitrogen and phosphorus loading calculations are performed using the LTIMP flow and nutrient concentration database. LTIMP also includes measurements of atmospheric deposition using wet/dry collectors and measurement of Secchi depth and associated limnological parameters (e.g., Byron and Goldman 1988).

Brief descriptions of the current TMDL projects that are being done in support of Phase Two of the Lake Tahoe TMDL are provided below:

Integrated Water Quality Management Strategy – The goals of the Integrated Water Quality Management Strategy project were twofold. First, the project considered the feasibility and potential effectiveness of different pollutant control measures for reducing pollutant loads from the major pollutant source categories. Second, the project packaged various load reduction opportunities into integrated implementation strategies. With feedback from the Pathway Forum and other stakeholders, the sample strategies were refined into a single Recommended Strategy for TMDL implementation.

Pollutant Load Reduction Model – A team of consultants lead by Northwest Hydrologic Consultants, Inc. and GeoSyntec is working to develop a modeling tool to estimate pollutant load reductions from water quality improvement actions at a subwatershed scale. It is expected that this tool will provide a uniform approach to calculating expected pollutant load reductions from infrastructure improvements, roadway management actions, and operations and maintenance practices. Load reduction estimates will help inform Lake Clarity Credit assignment assist in measuring progress towards achieving required pollutant load reductions.

Water Quality Crediting, Incentives, and Trading Feasibility Study – Environmental Incentives, LLC is working on behalf of the Lake Tahoe TMDL effort to establish a Lake Clarity Crediting Progam that will link water quality improvement actions to pollutant load reductions. The crediting system will primarily be used to evaluate and track load reductions from the urban source category. The program will ensure consistent water quality benefit assessments and will offer greater regulatory flexibility to municipal jurisdictions in selecting and implementing water quality improvement actions. The Crediting Program will also provide a consistent metric to determine compliance with municipal storm water regulations.

Load Reduction Accounting and Tracking System – A pollutant reduction tracking system is critical to water quality restoration in that it provides resource managers and project implementers with an up-to-date assessment of progress towards meeting the Lake Tahoe TMDL and associated pollutant load reduction allocations. These systems will allow for the tracking of trends and for modification of the implementation timeline based upon new information. In partnership with the United States Army Corp of Engineers, the Lahontan Water Board is developing a comprehensive Accounting and Tracking System database to support the Lake Tahoe TMDL and the Lake Clarity Crediting Program information storage and reporting needs. The Accounting and Tracking System will account for water clarity credits, track load reduction estimates, and provide ready access to tables and charts to document progress toward meeting pollutant load reduction goals. 2nd Nature, Inc. is leading the Accounting and Tracking System project team.

1.4 Problem Statement

Lake Tahoe is a unique environmental treasure, and designated by the State of California and the USEPA as an Outstanding National Resource Water (ONRW) under the Clean Water Act. However, Lake Tahoe's hydrologic and air basins are part of a changing landscape, with significant portions of this once pristine region now urbanized. Studies during the past forty years have shown that many factors have interacted to degrade the Lake Tahoe Basin's air quality, terrestrial landscape and water quality, such as land disturbance, increasing resident and tourist population, habitat destruction, air pollution, soil erosion, roads and road maintenance and loss of natural landscapes capable of detaining and infiltrating rainfall runoff (Goldman 1998, Reuter et al. 2003). Cumulatively, these factors have impacted the famed transparency of Lake Tahoe as indicated by the loss of approximately 8 meters of Secchi depth clarity since the early 1970s.

1.4.1 Nature of Impairment to Water Quality

Continuous long-term evaluation of water quality in Lake Tahoe between 1968 and 2008 has documented a decline of deep water transparency (commonly referred to as clarity) from an annual average of 31.2 meters to 21.2 meters, respectively (Jassby et al. 1999, 2003, UC Davis - TERC 2009). Transparency is expressed as Secchi depth and is the depth to which an observer can see a 25 centimeter diameter white disk lowered into the water from the surface. This long-term loss of transparency is both statistically significant ($p < 0.001$) and visually apparent.

Based on the most recent Secchi depth data for 2007 and applying a more sophisticated statistical approach known as a *generalized additive model*, it was recently reported that between 2001 and 2007 there was an apparent slowing in the rate of clarity loss (UC Davis - TERC 2008). Researchers caution that the trend developed by the current analysis could change depending on what future measurements show and the seven years of most recent data is insufficient to declare with certainty that the apparent slowing will be sustained into the future. Since even the most recent annual Secchi depth value of 21.2 meters as measured in 2008 is 8.5 meters less than the 1967-1971 average annual Secchi depth of 29.7 meters, the loss of transparency is a significant water quality impairment.

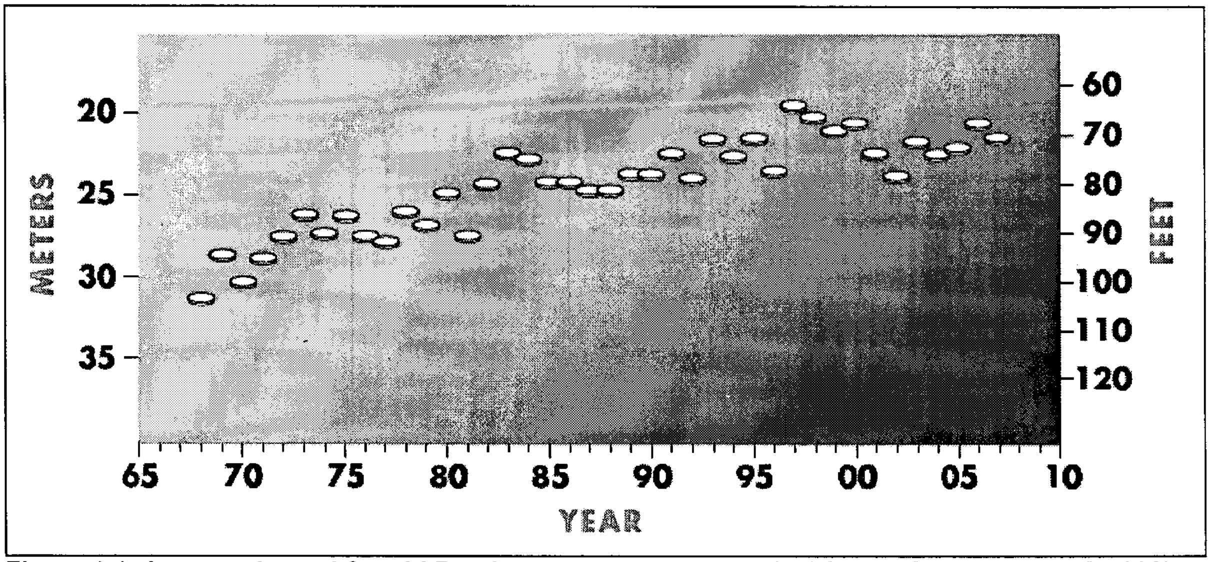

Figure 1-1. Average Annual Secchi Depth measurements (modified from UC Davis – TERC 2008).

Further signs of impairment to the waters of Lake Tahoe include these examples that add evidence that the water quality of Lake Tahoe has undergone significant changes:

- algal growth rate or primary productivity has increased since 1958 (e.g. Goldman 1998, Jassby et al. 2001, UC Davis - TERC 2009);
- the depth at which the deep chlorophyll maximum occurs has generally been getting shallower over time – presumably linked to the decline in clarity (UC Davis - TERC 2009);
- nuisance growth of attached algae is found in the urbanized nearshore region (e.g. Hackley et al. 2007);
- turbidity in the nearshore is elevated in the vicinity of urban regions compared to undeveloped land-uses (Taylor et al. 2003); and
- changes in lake biology and food web dynamics (e.g. Hunter et al. 1990, Zanden et al. 2003, Hunter 2004, Chandra et al. 2005).

The measurements shown in Figure 1-1 represent annual averages of Secchi depth measurements; Table 1-3 provides the specific data for each year in the long-term record. However, Secchi depth exhibits distinct seasonal changes. The mean seasonal pattern over the period of record is bimodal, with a strong annual minimum Secchi depth (reduced transparency) in May-June and a weaker local minimum in December (Jassby et al. 1999). The clearest water is typically observed in February with a secondary period of clear water in October.

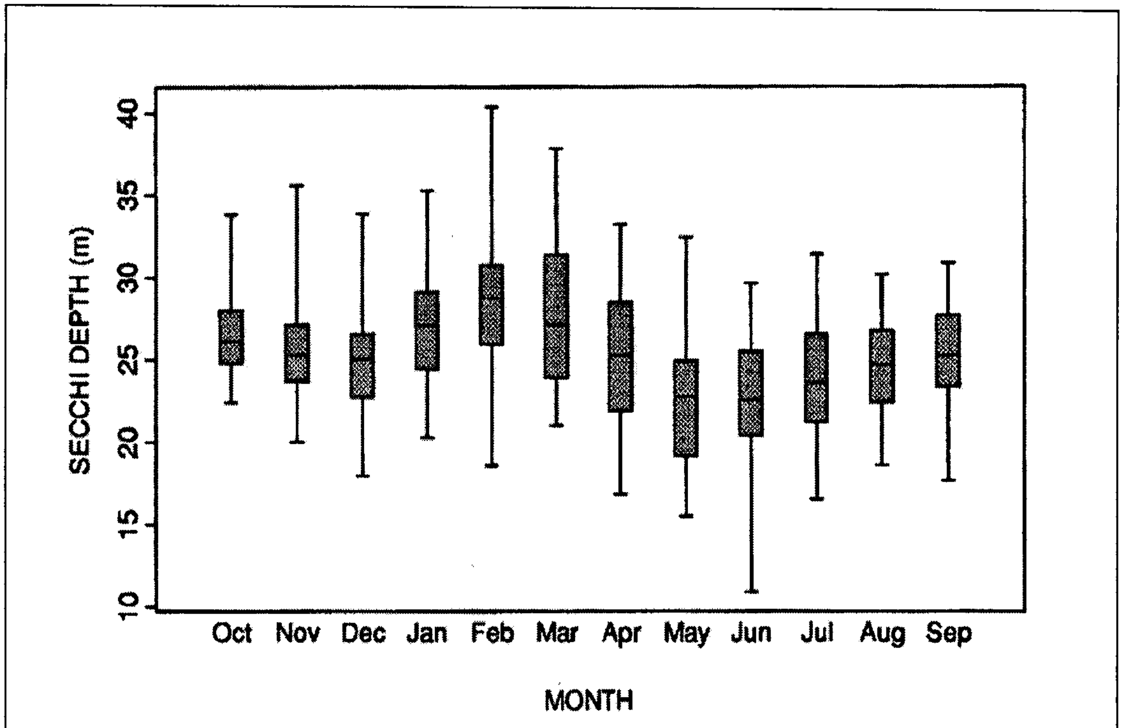

Figure 1-2. Seasonal pattern of Secchi depth from 1968-1996 (Jassby et al. 1999).

Jassby et al. (1999) considered the decreased Secchi depth in June to be due to the cumulative discharge of suspended sediment following melting of the seasonal snowpack. This is consistent with the measured seasonal pattern of suspended sediment discharge and with visual observations of sediment plumes entering the lake. The sediment load typically diminishes in June and thermal stratification with-in the lake intensifies. From June to October, the balance between watershed inputs and loss of particles from upper waters due to sedimentation begins to shift, resulting in the gradual increase in transparency. The December transparency minimum is attributed to the deepening of the mixed layer as the thermocline erodes at that time of year and passes through layers of phytoplankton and other light-attenuating particles that reach a maximum below the summer mixed layer (e.g., the deep chlorophyll maximum typically found between 40 – 60 meters in Lake Tahoe).

Table 1-3. Annual Average Secchi Depth values for the period of record (UC Davis – TERC unpublished). Measurements are made year-round at a rate of between 25 to 35 times per year.

Year	Secchi Depth (meters)	Year	Secchi Depth (meters)
1968	31.2	1989	23.6
1969	28.6	1990	23.6
1970	30.2	1991	22.4
1971	28.7	1992	23.9
1972	27.4	1993	21.5
1973	26.1	1994	22.6
1974	27.2	1995	21.5

1975	26.1	1996	23.5
1976	27.4	1997	19.5
1977	27.9	1998	20.1
1978	26.0	1999	21.0
1979	26.7	2000	20.5
1980	24.8	2001	22.4
1981	27.4	2002	23.8
1982	24.3	2003	21.6
1983	22.4	2004	22.4
1984	22.8	2005	22.1
1985	24.2	2006	20.6
1986	24.1	2007	21.4
1987	24.7	2008	21.2
1988	24.7		

In addition to the change in Secchi depth (transparency), there have been documented changes in the vertical transmission or penetration of light into the water (clarity). Light penetration (euphotic zone) in Lake Tahoe has been as deep as about 100 - 110 meters, but over the past decade it has largely ranged from 70 - 80 meters (Coon et al. 1987; UC Davis-TERC unpublished data). The uphotic zone is defined as the approximate depth where algal photosynthesis and respiration are equal and primary productivity goes to zero. Swift (2004) reported that the reduction in this deep-light transmission has caused an important upward shift of the deep chlorophyll maximum in Lake Tahoe from 60 – 90 meters in the early 1970s to 40 – 70 meters more recently. In addition to documenting changes to water quality, the gradual change to the euphotic zone affects pelagic and benthic food webs, (Chandra et al. 2005) as well as lake trout spawning habitat in deep-water aquatic plant communities (Beauchamp et al. 1992).

The declining transparency resulted in the inclusion of Lake Tahoe as water quality-limited in California's biennial report on water quality, as mandated by CWA Section 305(b), in 1998. That same year, Lake Tahoe was included on California's Section 303(d) list of waterbodies requiring development of TMDLs (SWRCB 2003). Lake Tahoe was also placed on Nevada's 2002 Section 303(d) list of impaired waters (NDEP 2002) as a result of clarity loss.

2 Numeric Target

The Clean Water Act (CWA) establishes a regulatory framework to restore degraded surface waterbodies. The framework begins with adoption by states, subject to USEPA approval, of appropriate numeric or narrative water quality standards for the subject waterbody. This includes designating the beneficial uses of the water, setting criteria necessary to protect the uses, and preventing degradation of water quality by means of antidegradation provisions. States adopt water quality standards to protect public health or welfare, to enhance the quality of water and to serve the purposes of the CWA by helping to "restore and maintain the chemical, physical and biological integrity" of state waters (CWA section 101(a)).

2.1 Applicable State and Regional Water Quality Standards

Consistent with the requirements of the CWA, beneficial uses, water quality criteria and antidegradation objectives have been established for Lake Tahoe by the States of California and Nevada. Additionally, the Lake Tahoe basin has water quality thresholds, programs and regulations as developed and implemented by the Tahoe Regional Planning Agency (TRPA). This section of the report summarizes the water quality standards of these regulatory agencies.

The primary responsibility for the protection of water quality in California rests with the State Water Resources Board (State Board) and nine Regional Water Quality Control Boards (Water Boards). The State Board sets statewide policy for the implementation of state and federal laws and regulations. The Regional Boards adopt and implement Water Quality Control Plans (Basin Plans). Basin Plans set forth water quality standards for the surface and groundwaters of the region, which include both designated beneficial uses of water and the narrative and/or numerical objectives that must be maintained or attained to protect beneficial uses. The Basin Plan implements a number of state and federal laws, the most important of which are the federal CWA and the State Porter-Cologne Water Quality Control Act (California Water Code § 1300 et seq). The jurisdiction of the California Regional Water Quality Control Board, Lahontan Region (the Water Board responsible for the Lake Tahoe basin) extends from the Oregon boarder to the northern Mojave Desert and includes all of California east of the Sierra Nevada crest.

The Nevada Water Pollution Control Law designated the Department of Conservation and Natural Resources (DCNR) as the State Water Pollution Control Agency for all purposes of the CWA. The statute authorizes the DCNR to assume the responsibilities delegated by federal water pollution control legislation and to develop comprehensive plans and programs for reducing or eliminating water pollution. Within DCNR, these functions and authorities are carried out by the Nevada Division of Environmental Protection (NDEP), which is the agency responsible for implementation of water quality protection programs and CWA requirements in the Lake Tahoe basin for the State of Nevada.

The Tahoe Regional Planning Compact was adopted in 1969 when the California and Nevada legislatures agreed to create the TRPA to protect Lake Tahoe. The Compact, as amended in 1980, defines the purpose of the TRPA (TRPA 1980):

> *To enhance governmental efficiency and effectiveness of the Region, it is imperative there be established a Tahoe Regional Planning Agency with the powers conferred by this compact including the power to establish environmental threshold carrying capacities and to adopt and enforce a regional plan and implementing ordinances which will achieve and maintain such capacities while providing opportunities for orderly growth and development consistent with such capacities.*

2.1.1 State Beneficial Uses

Table 2-1 provides a comparison of Lake Tahoe's beneficial uses as designated by California and Nevada. The two states' beneficial use designations are entirely consistent for purposes of establishing a TMDL to protect Lake Tahoe's transparency. Both California and Nevada have identified the aesthetic of Lake Tahoe's clarity as a beneficial use, "non-contact water recreation" in California and "recreation not involving contact with water" in Nevada.

Table 2-1. Comparison of Nevada and California beneficial uses for Lake Tahoe (LRWQCB 1995, Nevada Administrative Code).

Nevada	California
Irrigation	AGR – Agricultural Supply
Watering of Livestock	AGR – Agricultural Supply
Recreation not involving contact with the water	REC-2 – Non-contact Water Recreation
Recreation involving contact with the water	REC-1 – Water Contact Recreation
Industrial Supply	None
Propagation of wildlife	WILD – Wildlife Habitat
Propagation of aquatic life, including a coldwater fishery	COLD – Cold Freshwater Habitat
	BIOL – Preservation of Biological Habitats of Special Significance
	MIGR – Migration of Aquatic Organisms
	SPWN – Spawning, Reproduction and Development
Municipal or domestic supply, or both	MUN – Municipal and Domestic Supply
Water of extraordinary ecological or aesthetic value	Although not a Beneficial Use, California has designated Lake Tahoe an "Outstanding National Resource Water."
None	GWR – Groundwater Recharge
	NAV – Navigation
	COMM – Commercial and Sport Fishing

2.1.2 State Water Quality Objectives

Several water quality objectives serve to protect the non-contact recreation beneficial use, including clarity, transparency, algal productivity, and concentrations of nitrogen and phosphorus (LRWQCB 1995). Table 2-2 contains a comparison between California and Nevada's numeric water quality objectives related to clarity, and those factors that affect clarity and transparency.

Table 2-2. Comparison of Nevada and California numeric objectives for parameters related to lake clarity in Lake Tahoe (LRWQCB 1995, Nevada Administrative Code).

Parameter	Nevada[a]	California[b]
Soluble Phosphorus (mg/L)	Annual Average≤ 0.007	NA[c]
Total Phosphorus (mg/L)	NA[c]	Annual Average≤ 0.008
Total Nitrogen (as N) (mg/L)	Annual Average≤ 0.25 Single Value≤ 0.32	Annual Average≤ 0.15
Total Soluble Inorganic Nitrogen (mg/L)	Annual Average≤ 0.025	NA[c]
Algal Growth Potential	The mean annual algal growth potential at any point in the lake must not be greater than twice the mean annual algal potential at a limnetic reference station and using analytical methods determined jointly with the EPA, Region IX	The mean annual algal growth potential at any point in the lake must not be greater than twice the mean annual algal potential at a limnetic reference station. The limnetic reference station is located in the north central portion of Lake Tahoe. It is shown on maps in annual reports of the Lake Tahoe Interagency Monitoring Program. Exact coordinates can be obtained from the UC Davis Tahoe Research Group.
Plankton Count (No./mL)	Jun – Sep Average ≤ 100 Single Value≤ 500	Mean seasonal ≤ 100 Maximum ≤ 500
Biological Indicators	NA[c]	Algal productivity and the biomass of phytoplankton, zooplankton, and periphyton shall not be increased beyond the levels recorded in 1967-71 based on statistical comparison of seasonal and annual means. The "1967-71 levels" are reported in the annual summary reports of the "California-Nevada-Federal Joint Water Quality Investigation of Lake Tahoe" published by the California Department of Water Resources. [Note: The numeric criterion for algal productivity (or Primary Productivity, PPr) is 52 g C m^{-2} y^{-1} as an annual mean.]
Clarity	The vertical extinction coefficient must be less than 0.08 per meter when measured at any depth below the first meter. Turbidity must not exceed 3 NTU at any point of the lake too shallow to determine a reliable extinction coefficient.	The vertical extinction coefficient must be less than 0.08 per meter when measured at any depth below the first meter. Turbidity must not exceed 3 NTU at any point of the lake too shallow to determine a reliable extinction coefficient. In addition, turbidity shall not exceed 1 NTU in shallow waters not directly influenced by stream discharges. The Regional Board will determine when water is too shallow to determine a reliable vertical extinction coefficient based upon its review of standard limnological methods and on advice from the UC Davis Tahoe Research Group.
Transparency	NA[c]	The Secchi disk transparency shall not be decreased below the levels recorded in 1967-71, based on a statistical comparison of seasonal and annual mean values. The "1967-71 levels" are reported in the annual summary reports of the "California-Nevada-Federal Joint Water Quality Investigation of Lake Tahoe" published by the California Department of Water Resources. [Note: the 1967-71 annual mean Secchi depth was 29.7 meters.]

[a]Provision in State Regulation: Nevada Administrative Code 445A.191
[b]Provision in State Regulation: Water Quality Control Plan for the Lahontan Region (LRWQCB 1995).
[c]No applicable numeric water quality objectives

Transparency is best considered as a measure of visibility; that is, the depth to which one can see down into the water. The Secchi depth is the depth at which a 25 centimeter white disk is no longer visible from the surface as it is lowered into a waterbody. An observer lowers the Secchi disk into the water and records the depths at which it disappears then re-appears upon retrieval. The average of those two depths is considered the Secchi depth. The historical trend of declining transparency has been made using a 25 centimeter, all white, Secchi disk. The clear water of Lake Tahoe yields Secchi depths on the order of 20 - 30 meters and, therefore, this measure of transparency is not used in shallow, near-shore environments where the disk would be seen on the lake bottom.

The Vertical Extinction Coefficient (VEC) represents the fraction of light held back (or extinguished) in water per meter of depth by absorption and scattering (Goldman and Horne 1983). Thus, higher VEC values indicate less clarity. VEC was measured using a sensor that captures light in the range photosynthetically active radiation (400 – 700 nm). The vertical transmission or penetration of light down the water column extends beyond the Secchi depth and in Lake Tahoe very small amounts of light can be measured at depths greater than 100 meters (Swift 2004). The VEC numeric objective also protects deep light penetration (from 30 meters to approximately 100 meters), which is important for protecting deep living aquatic rooted plants (macrophytes) that serve as lake trout spawning and rearing grounds (Beauchamp et al. 1992). From 1967 to 2002 the VEC at Lake Tahoe, as measured by the UC Davis - TERC, has ranged from approximately 0.04-0.11/meter.

2.1.3 State Nondegradation Objectives

All California waterbodies are subject to an antidegradation objective that requires continued maintenance of high quality waters. In 1980 California's State Water Resources Control Board (SWRCB) designated Lake Tahoe as subject to the highest level of protection under the antidegradation objective, that of an ONRW, both for its recreational and its ecological value. The Water Board's Basin Plan states (LRWQCB 1995):

> *Viewed from the standpoint of protecting beneficial uses, preventing deterioration of Lake Tahoe requires that there be no significant increase in algal growth rates. Lake Tahoe's exceptional recreational value depends on enjoyment of the scenic beauty imparted by its clear, blue waters. Likewise, preserving Lake Tahoe's ecological value depends on maintaining the extraordinarily low rates of algal growth which make Lake Tahoe an outstanding ecological resource.*

Section 114 of the federal CWA also indicates the need to "preserve the fragile ecology of Lake Tahoe." The water quality of an ONRW must be maintained and protected under 40 CFR 131.12(a)(3). No permanent or long-term reduction in water quality is allowable for an ONRW.

Rather than designating Lake Tahoe an ONRW, Nevada has adopted the following beneficial use of Lake Tahoe: "water of extraordinary ecological or aesthetic value (Nevada Administrative Code (NAC) 445A.1905.)." There are significant differences between California's ONRW designation and Nevada's "water of extraordinary value" designation.

Nevada's numeric criteria for Lake Tahoe are essentially Requirements to Maintain Higher Quality (RMHQs). RMHQs are intended to protect water quality higher than that strictly necessary to support beneficial uses. According to CWA regulations at 40 CFR 131.12(a)(2), the RMHQ criteria "shall be maintained and protected unless the State finds that allowing lower water quality is necessary to accommodate important economic or social development in the area in which the waters are located." Therefore Nevada's antidegradation designation of Lake Tahoe affords less protection than does California's. However, the difference between California's and Nevada's designations does not diminish the prohibition against water quality reduction required by California's ONRW designation, because Lake Tahoe is an interstate waterbody where more stringent protections by one state dictate the overall requirements that pertain throughout the basin. This is because of 40 CFR Part 131.10(b), which states: "In designating uses of a waterbody and the appropriate criteria for those uses, the State shall take into consideration the water quality standards [WQS] of downstream waters and shall ensure that its WQS provide for the attainment and maintenance of WQS of downstream waters."

2.1.4 Tahoe Regional Planning Agency Water Quality Objectives

Article V(c)(1) of the Tahoe Regional Planning Compact calls for a "land use plan for the...standards for the uses of land, water, air space and other natural resources within the Region..." The Land Use Element includes the Water Quality sub-element, which is introduced with the following language (TRPA 1980):

> *The purity of Lake Tahoe and its tributary streams helps make the Tahoe basin unique. Lake Tahoe is one of the three clearest lakes of its size in the world. Its unusual water quality contributes to the scenic beauty of the Region, yet it depends today upon a fragile balance among soils, vegetation, and man. The focus of water quality enhancement and protection in the basin is to minimize man-made disturbance to the watershed and to reduce or eliminate the addition of pollutants that result from development.*

The TRPA Compact established several policies related to water quality planning and implementation programs. Relative to standards, the Compact states that the Regional Plan shall provide for attaining and maintaining federal, state or local water quality standards, whichever are the most stringent.

In addition to the establishment of Numerical, Management and Policy standards for water quality, there are two water quality goals:

> *GOAL #1: Reduce loads of sediment and algal nutrients to Lake Tahoe; Meet sediment and nutrient objectives for tributary streams, surface runoff, and sub-surface runoff, and restore 80 percent of the disturbed lands.*
>
> *GOAL #2: Reduce or eliminate the addition of other pollutants that affect, or potentially affect, water quality in the Tahoe basin.*

To achieve these goals, the TRPA established a number of supporting standards and indicators that include numeric objectives for protection of lake clarity. The relevant standards and indicators are listed below.

WQ-1 Littoral (Nearshore) Lake Tahoe

> Threshold Standard: Decrease sediment load as required to attain turbidity values not to exceed 3 NTU in littoral Lake Tahoe. In addition, turbidity shall not exceed 1 NTU in shallow waters of Lake Tahoe not directly influenced by stream discharge.
>
> Indicator: Turbidity offshore at the 25-meter depth contour at 8 locations, both near the mouths of tributaries and away from the tributaries.

WQ-2 Pelagic Lake Tahoe, Deep Water

> Threshold Standard: Average Secchi depth, December – March, shall not be less than 33.4 meters.
>
> Indicator: Secchi depth, winter average; Tahoe Research Group index stations (meters).

It should be noted that there is a difference between the California and TRPA objectives for transparency relevant to Secchi measurement. The TRPA uses a winter (December – March) average while California uses a statistical comparison of seasonal and annual mean values.

2.2 Comparison of Water Quality Objectives and Determination of Numeric Target

The objective of the Lake Tahoe TMDL is to restore the deep water transparency and clarity of Lake Tahoe to levels protected by California, Nevada and TRPA water quality standards (Table 2-2). As described in Sections 2.1.1 and 2.1.4, all three of these agencies have identified the aesthetic quality of Lake Tahoe's deep water clarity as a beneficial use and all three accord Lake Tahoe a high level of protection against degradation. Section 2.2 compares these water quality objectives and provides an appropriate numeric target for the TMDL.

2.2.1 Comparison of Lake Tahoe Transparency and Clarity Objectives

Clarity and transparency standards are both used to protect the aesthetic beneficial use of water in Lake Tahoe (Table 2-2). Clarity standards, in both California and Nevada, are expressed as the VEC of light as it penetrates down into the Lake's water column, and as turbidity in littoral (nearshore) areas too shallow to reliably determine a VEC. California also has adopted a transparency objective for the deep water lake that is based on Secchi disk measurements. Nevada has not yet adopted a numeric objective for transparency; however, it has committed to begin addressing such an adoption following the TMDL process.

The State of California's transparency objective for Lake Tahoe is based on a statistical comparison of the seasonal and annual mean Secchi depth values measured from 1967-1971. The TRPA has an objective of 33.4 meters Secchi depth, winter average (December – March). The States of California and Nevada have adopted the same clarity objectives for the pelagic portion of the lake, which is a VEC that must be less than 0.08 per meter when measured at any depth below the first meter. Given that the California transparency objective protects the lake's historical condition that predates both the CWA and applicable dates established in federal regulation for protection of existing uses (November 28, 1975, per 40 CFR 130.26), the TMDL will assume that achieving the transparency objective, whichever is more protective, will also satisfy antidegradation requirements.

To determine the most appropriate numeric target for the Lake Tahoe TMDL, it was necessary to determine the relationship between Secchi depth and VEC values and evaluate which is more protective. The difference between California and TRPA clarity objectives was also assessed.

The relationship between VEC and Secchi depth readings in Lake Tahoe was examined for the periods 1967-2002 (Swift 2004). Between 1967-1971, the period upon which transparency objectives are based, Secchi depths were in the range of 28.5 - 32.5 meters and, in general, corresponded to VEC values between approximately 0.045 - 0.065 per meter. During 1967-1971 a VEC of ≥ 0.08 per meter was measured only three times in close to 100 observations. From 1972 to 2002, VEC in the deep water has varied from about 0.04 to 0.11 per meter, with annual values of approximately 0.06 per meter between 1968 and 1976 and annual values of 0.08 - 0.09 per meter during the period 1997-2002 (Swift 2004). Swift (2004) highlights the fact that VEC data collected from 1997 to 1983 was suspect due to an uncertain response in the submersible sensor. At no time between 1967 and 2002 did a VEC of 0.08 per meter correspond to a Secchi depth of 30 meters. A more appropriate value for VEC that reflects actual conditions from 1967-1971 would be on the order of 0.05 - 0.06 per meter. These observations show that the California water quality objective for average annual transparency (i.e. Secchi depth) is more protective than the California and Nevada clarity objective (VEC).

The TRPA winter Secchi depth objective of 33.4 meters (December-March) reflects the observation that measured light transmission is at its maximum during this season (Jassby et al. 1999). While it is acknowledged that the winter threshold is protective of water clarity at that time, it does not include the entire year. There is no reason why the winter period represents a special time when it would be more desirable to be protective of clarity. For the purpose of aesthetic enjoyment, the summer is the season when most visitors view the lake.

The seasonal variability in Secchi depth measurements is complicated by several factors unrelated to seasonal pollutant loading. Due to the limited amount of seasonal stormwater data available, the challenges associated with estimating loads and load reductions on a seasonal basis, and the complexity of Lake Tahoe's thermal and hydro dynamic properties, the numeric target for the Lake Tahoe TMDL relies on the average annual value and not seasonal average values.

2.2.2 Determination of Numeric Target

UC Davis scientists calculate the annual average Secchi depth by using a method commonly referred to as trapezoidal integration. First, linear interpolation is used between sampling points (Secchi depth measurements) to compute daily values. Then the daily values are summed for the year and divided by the number of days in the year to derive the annual average Secchi depth (Arneson 2010 personal communication).

The objective of this Lake Tahoe TMDL is to achieve the transparency (Secchi depth) and clarity (VEC) standards, but the California deep water transparency standard is the most protective. The Lake Tahoe TMDL numeric target is 29.7 meters average annual Secchi depth, which is the most protective target for deep water to approximately 30 meters of depth. For that area between 30 meters and approximately 100 meters, the UC Davis - TERC data shows that by attaining the 29.7 meter numeric target for transparency, the VEC (clarity) should always be < 0.08 per meter. Therefore a 29.7 meter Secchi depth should be protective of both transparency and clarity for Lake Tahoe's deep water.

3 Watershed and Lake Characteristics

This section of the report is intended to provide background information on Lake Tahoe and its watershed. This section is intended to help inform the reader about watershed and lake characteristics and how these characteristics influence pollutant loading and ultimately lake clarity. The first half of this section focuses on watershed and climactic conditions of the Tahoe basin while the second half focuses on how pollutants affect the optical properties of the lake.

3.1 Study Area

Lake Tahoe is situated near the crest of the Sierra Nevada range at an elevation of 6,224 feet (1,897 meters) above sea level. It is approximately 22 miles (35.5 km) at its longest point from north to south and 12 miles (19.3 km) at its maximum width, east to west. The drainage area is 200,650 acres (812 km^2) with a lake surface area of 123,800 acres (501 km^2) producing a watershed-to-lake ratio of only 1.6:1, much smaller than found in many other typical watersheds. Consequently, a significant amount of precipitation falls directly on Lake Tahoe. The California–Nevada state line splits the Lake Tahoe basin, with about three-quarters of the basin's area and about two-thirds of the lake's area lying in California (Figure 3-1). The geologic basin that cradles the lake is characterized by mountains reaching over 4,003 feet (1,220 meters) above lake level, steep slopes and erosive, granitic soils, although volcanic rocks and soils are also present in some areas. Slopes rise quickly from the lake's shore, reaching 30 to 50 percent in many places.

Lake Tahoe is the eleventh-deepest lake in the world with a maximum depth of 1,657 feet (505 meters). The average depth of the lake is 1,027 feet (313 meters). The surface area of the lake covers nearly two-fifths of the Lake Tahoe basin, and the lake holds nearly 39 trillion gallons of water. The hydraulic residence time is 650 years, which means that it takes, on average, 650 years for water that enters the lake to leave the lake. As a result of its volume, depth and geographic location, Lake Tahoe remains ice-free year-round, though Emerald Bay has frozen over during some extreme cold spells.

Lake Tahoe's current trophic status is oligotrophic, although clarity measurements and calculations of its vertical light extinction indicate the onset of cultural eutrophication (Goldman 1988).

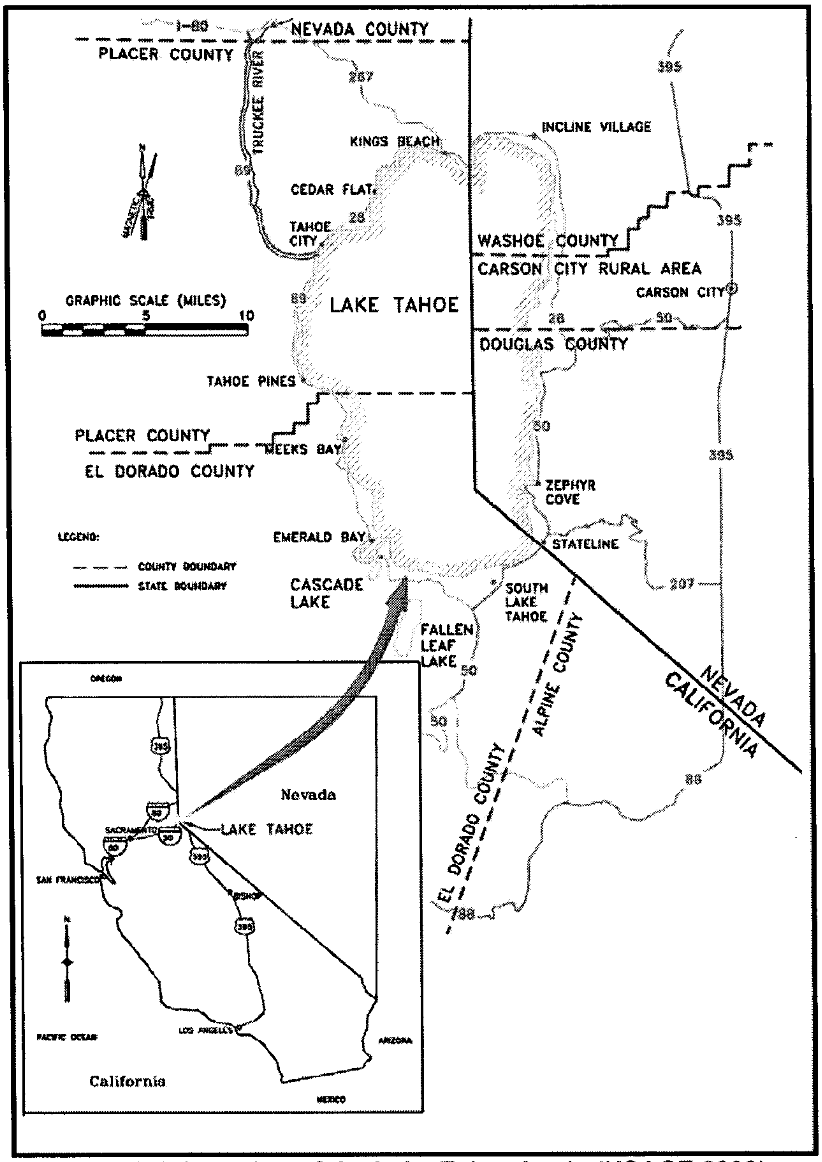

Figure 3-1. Location of the Lake Tahoe basin (USACE 2003).

Lake Tahoe is fed by 63 tributary streams. The largest tributary to Lake Tahoe is the Upper Truckee River, which contributes approximately 25 percent of the annual flow. The Lake Tahoe basin also has 52 intervening zones that drain directly to the lake without first entering streams. The lake has one outlet on its northwest side, forming the start of the Truckee River, which ultimately drains to Pyramid Lake, a terminal lake located in Nevada.

In 1874, a timber dam was built to regulate water outflow at the Truckee River outlet in Tahoe City, California. The timber dam was partially removed in 1909 and construction began on a new concrete dam. The concrete dam was completed in 1913 and later in 1988 it was seismically retrofitted and enlarged to its current configuration. In 1915, a federal court placed the dam under federal control. Up to the level of the natural rim

(6223, Lake Tahoe datum), Tahoe water is unavailable for downstream use. The maximum water level was set at 6,229.1 feet and the lake's natural rim elevation was set at 6,223.0 feet (Lake Tahoe Datum) in 1935 pursuant to the Truckee River Operating Agreement (TROA). These elevations were affirmed through a court case that resulted in the Orr Ditch Decree (September 8, 1944). According to Boughton et al. (1997) the upper six feet of the lake forms the largest storage reservoir in the Truckee River basin, with an effective capacity of 240 billion gallons (745,000 acre-feet). Since 1987, lake levels have fluctuated from 6,220.26 feet (about 3 feet below the rim), during a prolonged drought in 1992 to 6,229.39 feet (about 0.2 feet above the legal maximum), during the flood of January 1997(Boughton et al. 1997).

The lake's montane-subalpine watershed is predominantly vegetated by mixed coniferous forests, although bare granite outcrops and meadows are also common features. Most urban development exists along the lake's shoreline, with the largest concentrations occurring at South Lake Tahoe in the southeast, Tahoe City in the northwest and Incline Village in the northeast. The north and west shores are less densely populated, and the east shore is mostly undeveloped.

3.2 Watershed Characteristics

3.2.1 Geology and Soils

The Lake Tahoe basin was formed approximately 2 to 3 million years ago by geologic faulting that caused large sections of land to move up and down. Uplifted blocks created the Carson Range on the east and the Sierra Nevada on the west while down-droppedblocks created the Lake Tahoe basin in between. About two million years ago, lava from Mt. Pluto on the north side of the basin blocked and dammed the northeastern end of the valley and caused the Lake Tahoe basin to gradually fill with water. As the lake water level rose, the Truckee River eroded an outlet and a stream course through the andesite (volcanic rock) flows down to the Great Basin hydrologic area to the east. Subsequent glacial action (between 2 million and 20,000 years ago) temporarily dammed the outlet causing lake levels to rise as much as 600 feet above the current level. A detailed account of the basin's geology and its effect on groundwater flow and aquifer characteristics is given by USACE (2003).

Nearly all the streams in the Tahoe basin lie on bedrock, with the exception of the south shore area and some other aquifers associated with the lower reaches of some streams. While Loeb (1987) found that the aquifers for the Ward Creek, Trout Creek and Upper Truckee River watersheds were sloped toward the lake (implying a net flow into the lake), some recent studies in the Pope Marsh area of the south shore indicate that under the influence of water pumping and seasonal effects, the net flow in some areas may be from the lake into the adjacent aquifer system (Green 1998, Green and Fogg 1998).

Lake Tahoe basin soils are generally low nutrient granitic soils, with more nutrient rich volcanic soils located in the north and northwestern parts of the basin. Soils near the lake consist of alluvial wash deposits (Crippen and Pavelka 1970). Soils in the basin have a wide range of erosion potential and soil permeability ranges from moderate to very rapid, with the lowest permeabilities found in the northwest quadrant of the basin (Tetra Tech 2007). Figure 3-2 presents a map of the general geology of the Lake Tahoe basin.

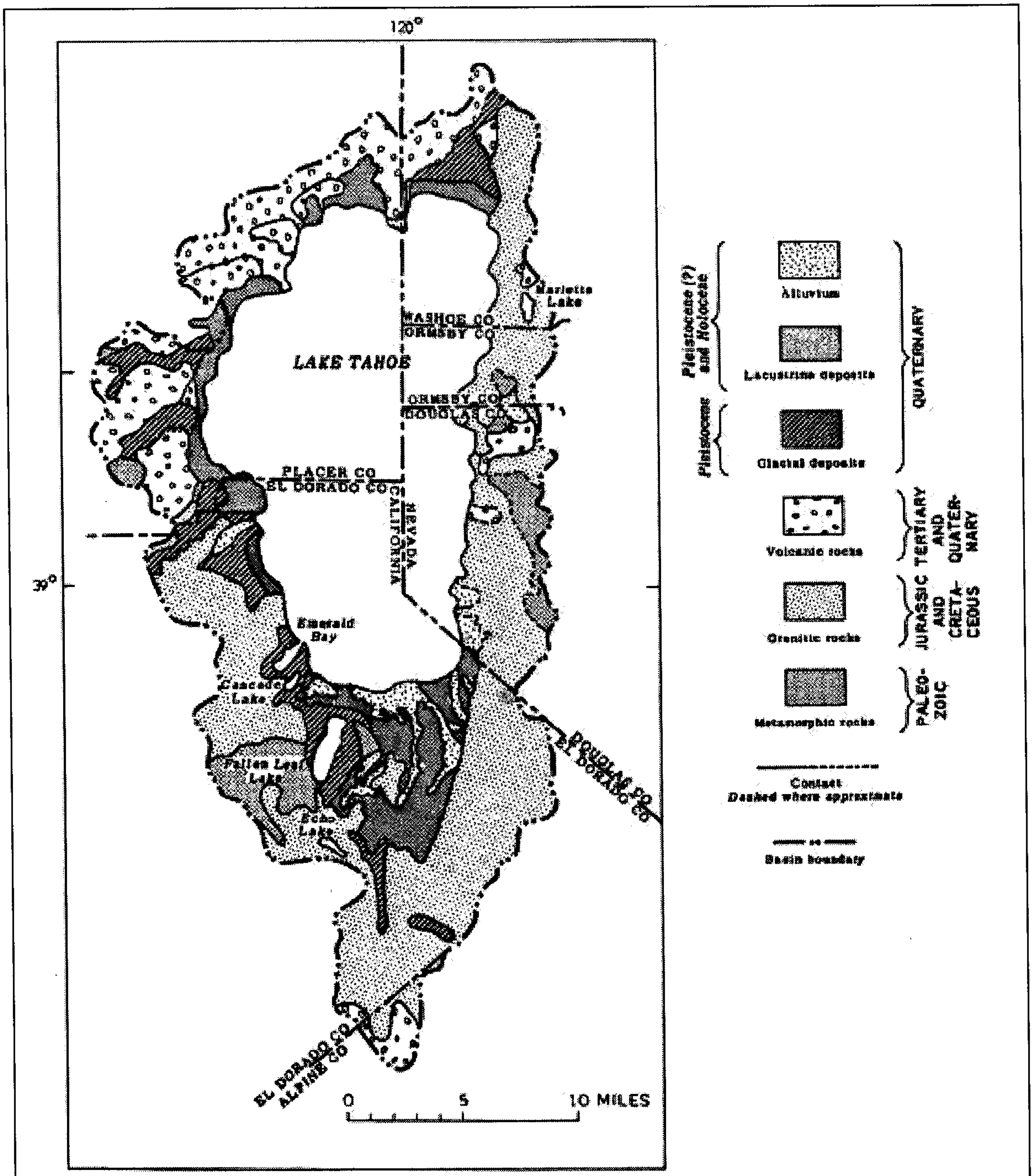

Figure 3-2. General geology of the Lake Tahoe basin (Crippen and Pavelka 1970). Note Ormsby Co should read Carson City Rural on the map.

3.2.2 Land-uses

Land-uses in the Lake Tahoe basin have an influence on the watershed, lake clarity, and other environmental attributes. A detailed natural and human history of the basin is provided in the *Lake Tahoe Watershed Assessment* (USDA 2000). Several significant, anthropogenic influences in the watershed followed its discovery by European-American explorers in 1844: clear-cut logging of an estimated 60 percent of the basin during the Comstock-era (1870s-1910s), livestock grazing (1900s-1950s), gradual urbanization of the lakeshore and lowest-lying parts of the basin beginning in the 1950s (USDA 2000), and public acquisition and protection of thousands of acres of sensitive lands since the mid-1960s. As of 1996 public ownership represented 85 percent of the total land area of the basin.

Based on available information, the land-uses in the basin were divided into six general categories:

- Single-family residential (SFR)
- Multi-family residential (MFR)
- Commercial/Institutional/Communications/Utilities (CICU)
- Roads (primary, secondary and unpaved)
- Vegetated
- Waterbody

The first three land-use categories (SFR, MFR, and CICU) were additionally broken down to pervious and impervious land-uses based upon IKONOS™ satellite imaging (Minor and Cablk 2004). The vegetated land, which makes up more than 80 percent of the watershed, was further broken down into undeveloped forest, turf, recreational, ski areas, burned and harvested vegetation. Simon, et al. (2003) divided the undeveloped forest into five erosion potential classes. A GIS layer developed as part of this report (Figure 3-3) shows that two percent of the total basin land area is impervious. This equates to over 5,000 impervious acres (Minor and Cablk 2004), many of which are adjacent to the lake or its major tributaries. At the same time, 14 of the 63 individual watersheds have 10 percent or more of their total land area as impervious coverage. The land-use map (Figure 3-3) and associated information in a geographic information system (GIS) database is available in more detail in Tetra Tech (2007).

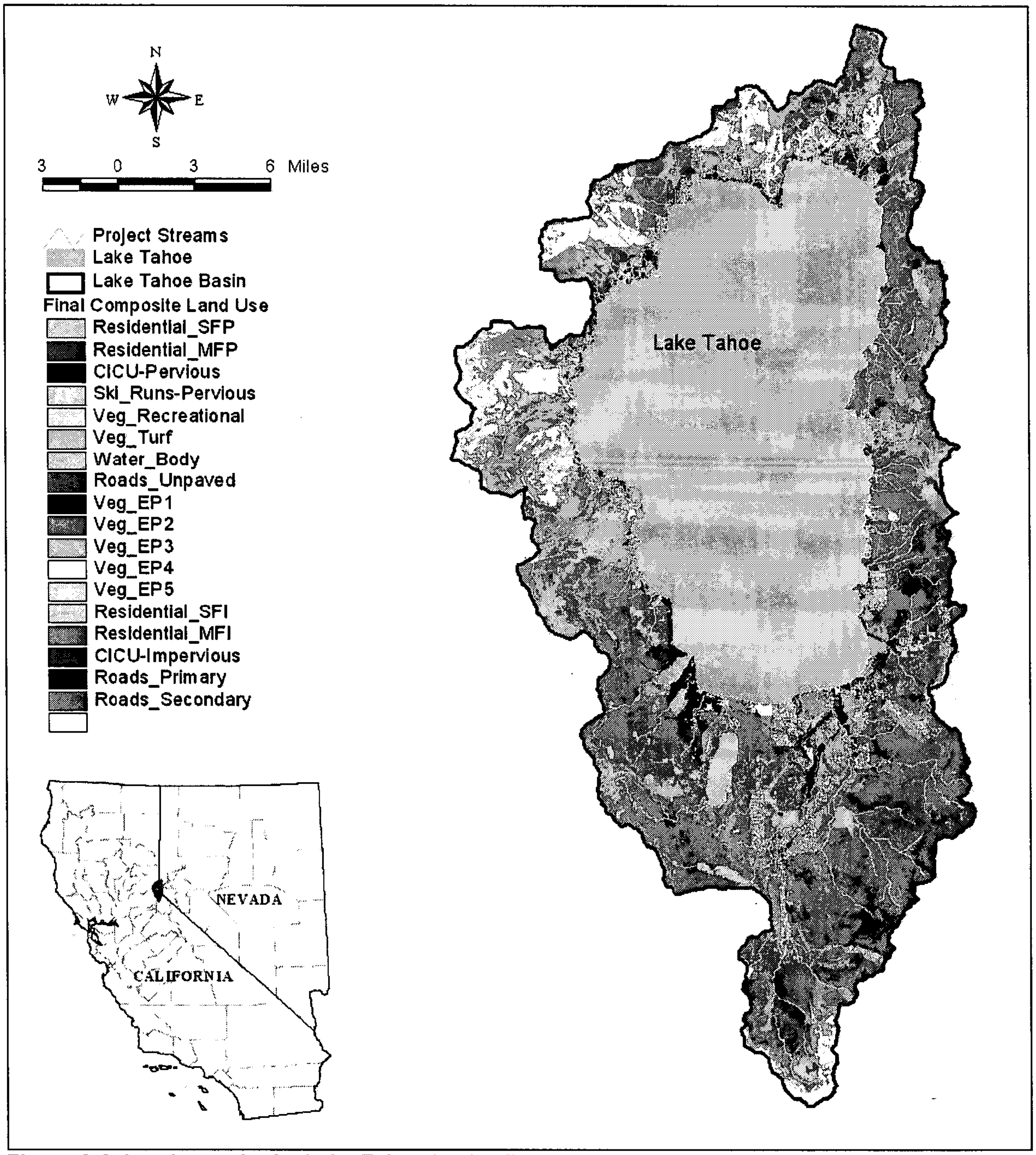

Figure 3-3. Land-uses in the Lake Tahoe basin (Tetra Tech 2007).

3.2.3 Climate and Hydrology

Climate is the single most important factor influencing pollutant delivery to Lake Tahoe as precipitation drives mobilization and transport of pollutants off the watershed and into tributaries and/or the lake. Most of the precipitation in the Lake Tahoe basin falls between October and May in the form of snow at higher elevations and snow/rain at lake level, which typically melts and runs off in May and June. However, precipitation timing can vary significantly from year to year (Coats and Goldman 2001, Rowe et al. 2002). Figure 3-4 is a plot of the monthly flow from the Upper Truckee River as an example of runoff seasonality. Watershed elevations differences also have a significant influence on the type of precipitation (snow or rain) and the timing of snow melt. For example, snow pack at lower elevations near the lake shore typically melts earlier, and can even melt off mid-winter if air temperatures and solar radiation conditions are right. It is common for the lower elevation snow pack to have melted completely before the tributaries crest with snowmelt from the higher and colder elevations.

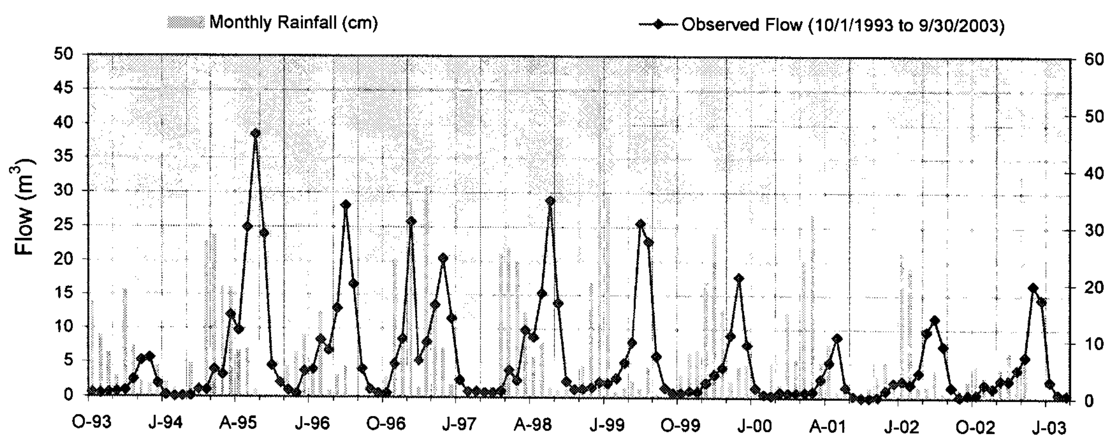

Figure 3-4. Monthly flow from the Upper Truckee River.

Summer thunderstorms, fall rain storms on bare ground, and rain-on-snow events also contribute to erosion, runoff, and pollutant transport into Lake Tahoe tributaries and/or the lake. The most significant hydrologic events typically accompany large rain-on-snow events, such as what happened in January 1997 when stream channels underwent major geomorphic changes (Simon et al. 2003) from the high runoff volume in a short time. Compared to spring snow melt and rain-on-snow events, summer thunderstorms typically are not responsible for significant pollutant loads to the tributaries (Hatch et al. 2001, S. Hackley unpublished data). Thunderstorms, however, can be intense and are capable of generating large loads for short periods of time, typically in isolated geographic locations.

Because the lake surface area is relatively large compared to its watershed area, a significant amount of precipitation (36.2 percent) enters the lake directly as snow or rain. Over 75 percent of the basin's precipitation is delivered by frontal weather systems from the Pacific Ocean between November and March. Topography largely determines the spatial distribution of precipitation and whether winter precipitation occurs as rain or snow. Lower elevations receive about 20 inches (500 mm) of annual precipitation, but the upper elevations on the west side of the basin receive about 59 inches (1,500 mm) (USDA 2000). Future climate change could cause both the relative distribution of snow versus rain and the distribution and extent of precipitation to change.

3.3 Precipitation Characteristics

This section briefly describes seasonal patterns in annual rain and snowfall, synoptic differences over the lake, and characteristics of the long-term data set.

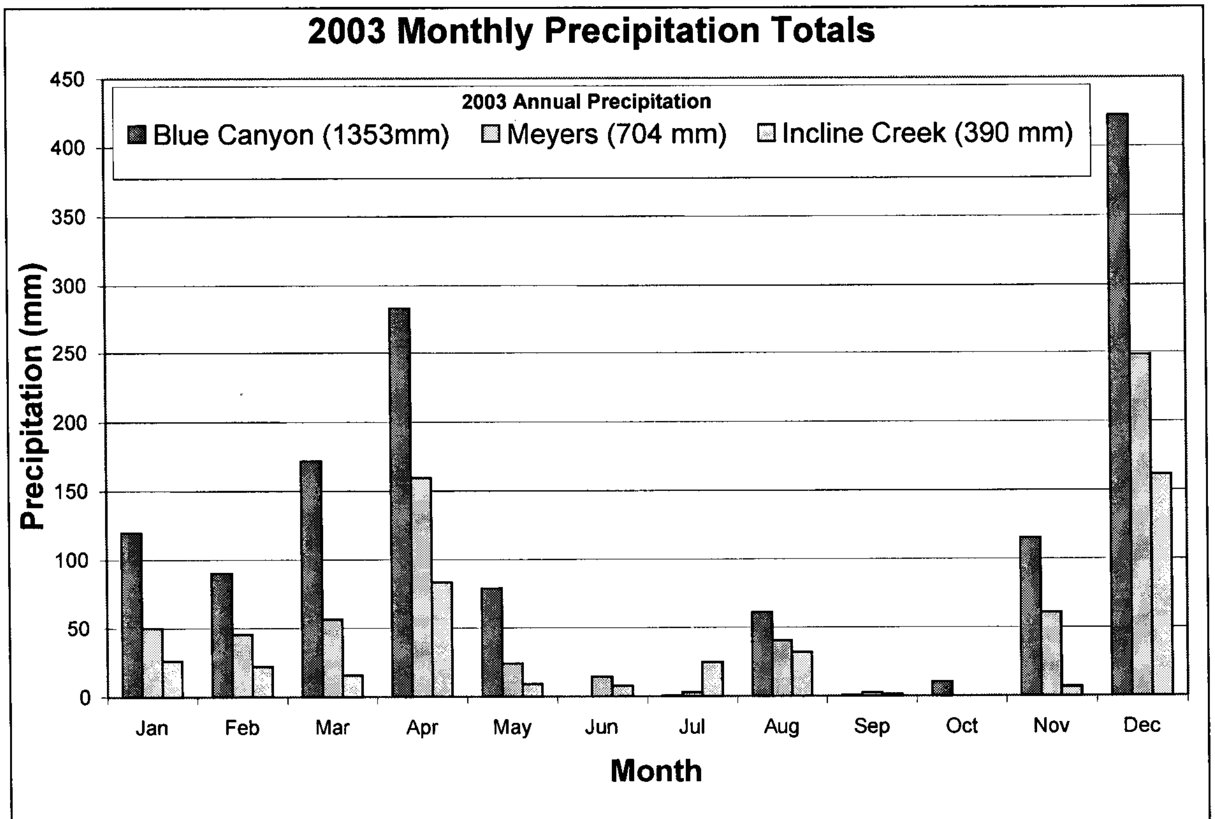

Figure 3-5. Monthly precipitation (2003) showing wet winters and dry summers (modified from CARB 2006).

Figure 3-5 presents precipitation from the CARB (2006) studies for 2003 showing the seasonal distribution of precipitation. Blue Canyon is on the west slope of the Sierra Nevada at an elevation of approximately 5,000 feet (outside the Tahoe basin). Meyers and Incline Creek are both located in the basin. All three stations exhibit the Mediterranean-type climate characterized by wet winters and dry summers. Even though intensive, short-duration thunderstorms occur during the summer, the July through September events contribute little to annual precipitation.

The isohyetal map (Figure 3-6) shows contours of mean annual precipitation in the basin, as well as, spatial differences in precipitation. A well-defined rain-shadow exists across the lake from west to east (Crippen and Pavelka 1970, Sierra Hydrotech 1986, Anderson et al. 2004). Precipitation over the lake declines from a value of about 35 inches/year (90 cm/year) along the west shore to 20 inches/year (51 cm/year) on the east shore. Annual averages include both snow and rain combined.

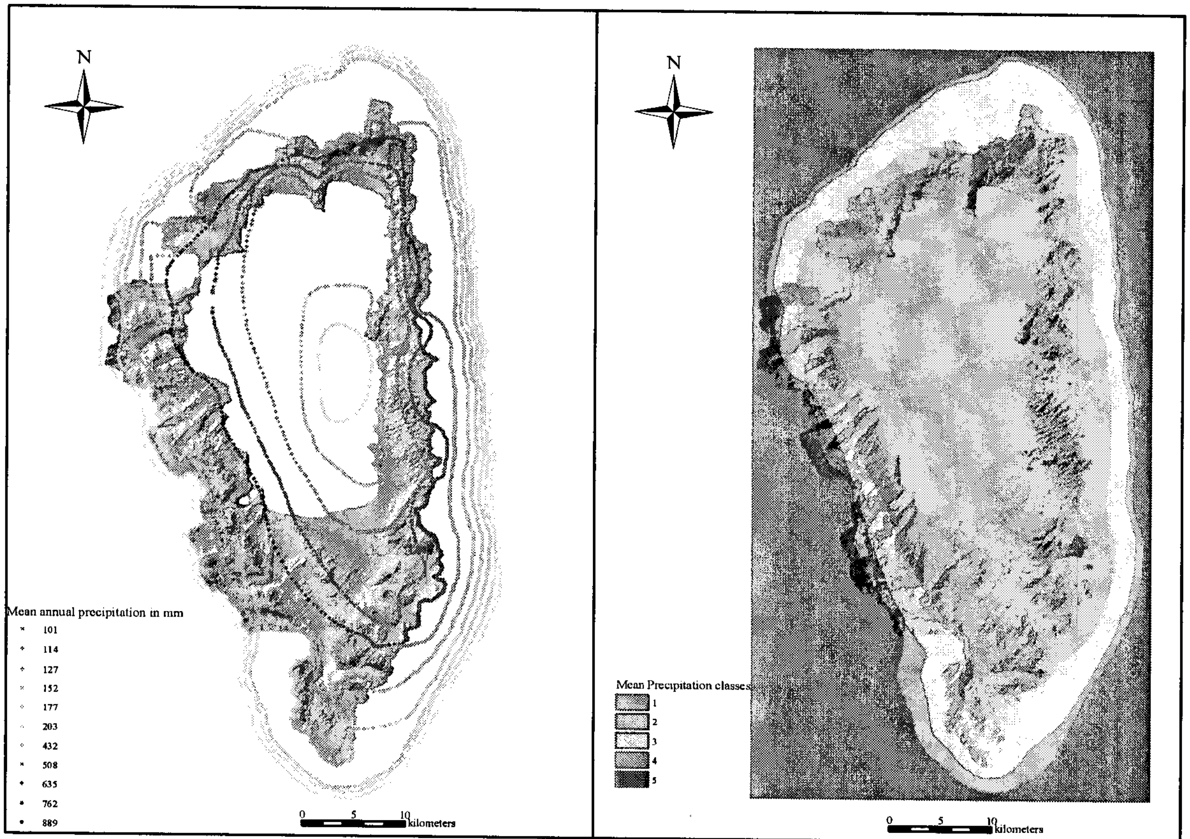

Figure 3-6. Isoheytal map for the Lake Tahoe basin showing contours of equal annual precipitation (Simon et al. 2003).

Year-to-year patterns of precipitation at Lake Tahoe can be seen from the 96-year data record (1910-2005) at Tahoe City, located in the northwest quadrant of the basin adjacent to the Truckee River outlet (Figure 3-7). Interannual and decade-scale patterns can be seen, which illustrate the variation that can occur from year to year. Typically, values are presented as precipitation totals in a water year, which is October 1 to September 30.

Mean annual precipitation during this period is 31.5 inches (80 cm) with a very similar median value of 30 inches (77 cm). The middle quartile values (25 – 75 percent of observations) are 3 – 38 inches/year (8.5 – 96.5 cm/year). Years with greater than 30 inches (77 cm) of precipitation occur regularly and typically not more than three consecutive years elapse without annual precipitation exceeding the median of approximately 30 inches/year (77 cm/year).

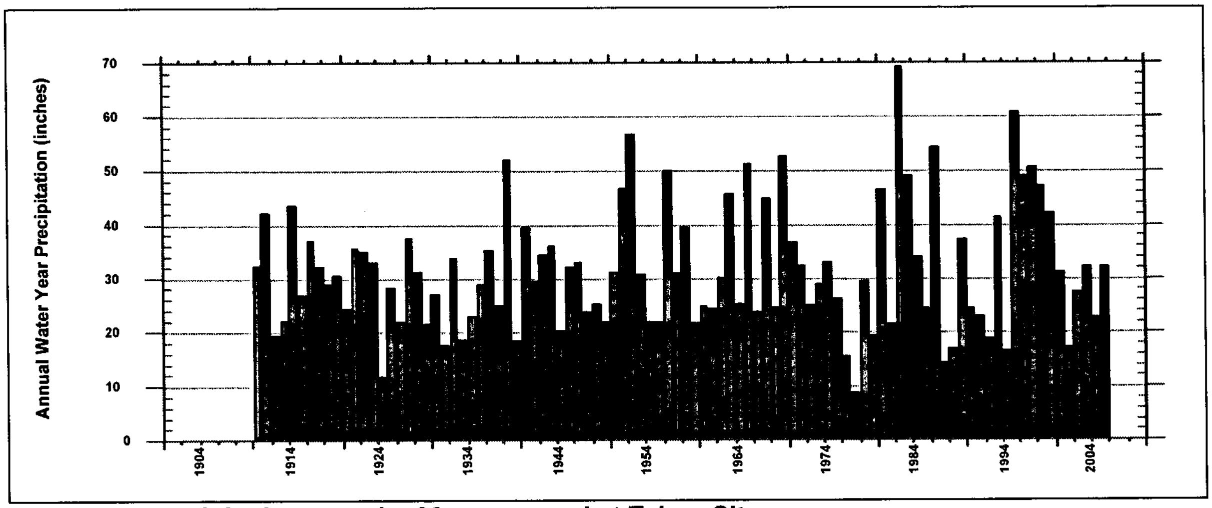

Figure 3-7. Precipitation over the 96-year record at Tahoe City.

3.4 Limnology and Optical Properties of Lake Tahoe

Limnology is the study of lakes and is concerned with the fundamental relationships and productivity of aquatic communities as they are affected by their physical, chemical and biotic environment (Wetzel 1983). The limnology of Lake Tahoe has been the subject of extensive research and the clarity has been a focus for many years. Lake clarity is a function of the water column's optical properties. This section focuses on some of the important issues related to the optical properties affecting Lake Tahoe's water clarity: nutrients, floating algae or phytoplankton, inorganic particles, and lake mixing.

3.4.1 Optical Properties in the Deep Water of Lake Tahoe

Light is absorbed and scattered as it travels through water. The optical properties of water can be divided into apparent and inherent properties. Apparent optical properties are a function of natural lighting and are influenced by sun angle, cloud cover and water surface conditions such as waves. Inherent optical properties depend on the water and the material contained in the water column. An important inherent optical property of water is light attenuation, which is a result of absorption and scattering of light.

Particles in water both absorb and scatter light. In Lake Tahoe, light scattering and absorption are caused by mineral and organic particles. Absorption also occurs from colored dissolved organic material (CDOM), such as naturally occurring tannins, humics and anthropogenic compounds that enter the lake (Taylor et al. 2003, Swift 2004). It should be noted that while absorption of light by CDOM was measureable in Lake Tahoe, it was a small portion of lake transparency loss in comparison to the fine sediment particles (Swift et al. 2006). CDOM was included in the optical component of the Lake Clarity Model. Also, water molecules themselves absorb and scatter light. Since the contribution of CDOM to light attenuation is so minor at Lake Tahoe and attenuation due to water molecules is an inherent characteristic of all waters, scattering and absorption by particles is dominant in Lake Tahoe. This can be seen in recent

Secchi depth data collected in Lake Tahoe (Figure 3-8). These data show the significant, albeit non-linear, relationship between the measured number of particles in Lake Tahoe and the corresponding Secchi depth (Swift 2004).

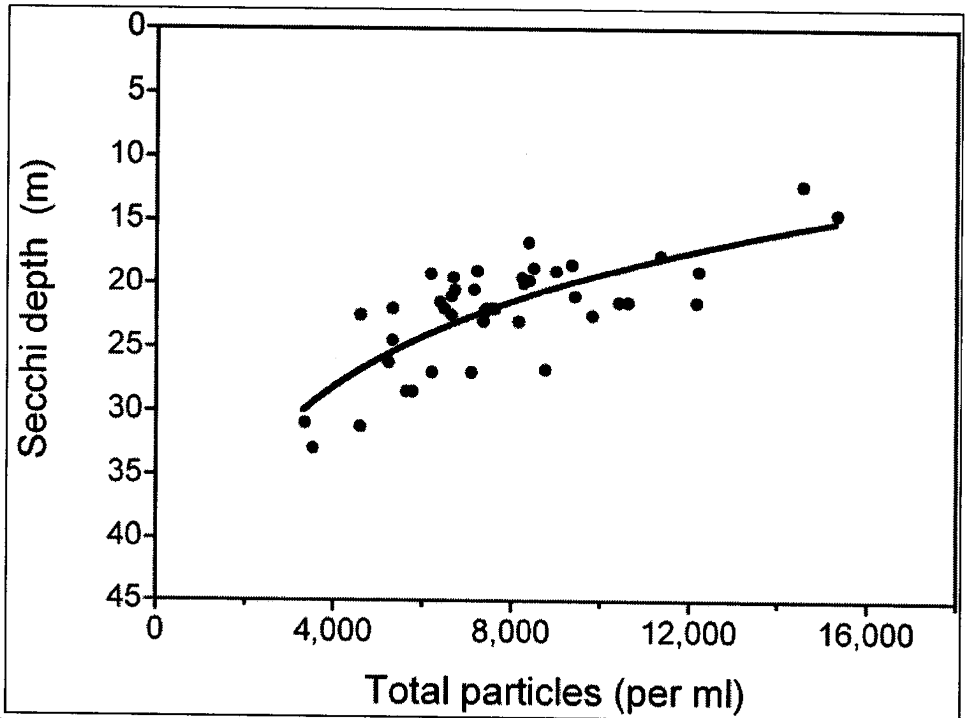

Figure 3-8. Relationship between in-lake particle number (< 16 µm) and Secchi depth (P 0.001 R^2 = 0.57) (modified from Swift 2004).

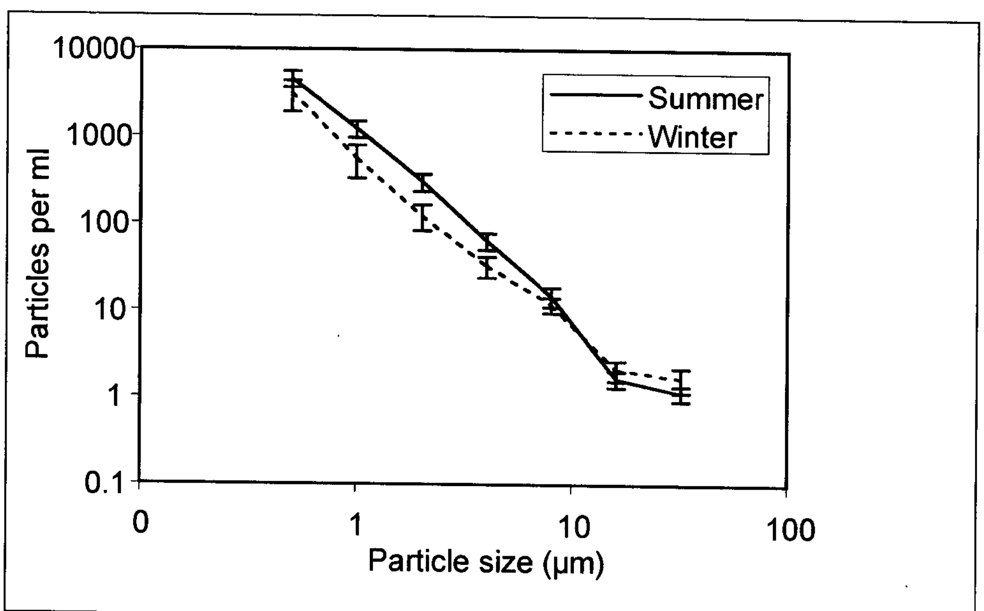

Figure 3-9. Particle size distribution in Lake Tahoe showing dominance of particles < 16 µm in diameter (Swift et al. 2006).

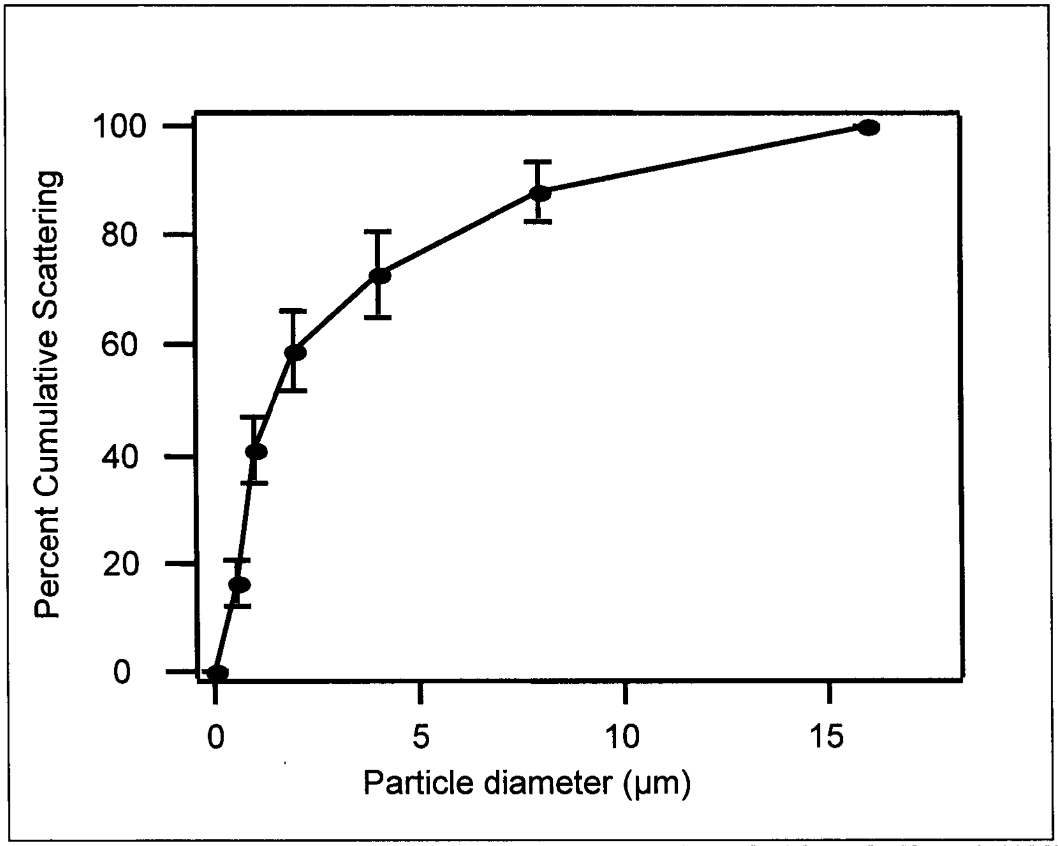

Figure 3-10. Influence of particle size on light scattering (modified from Swift et al. 2006).

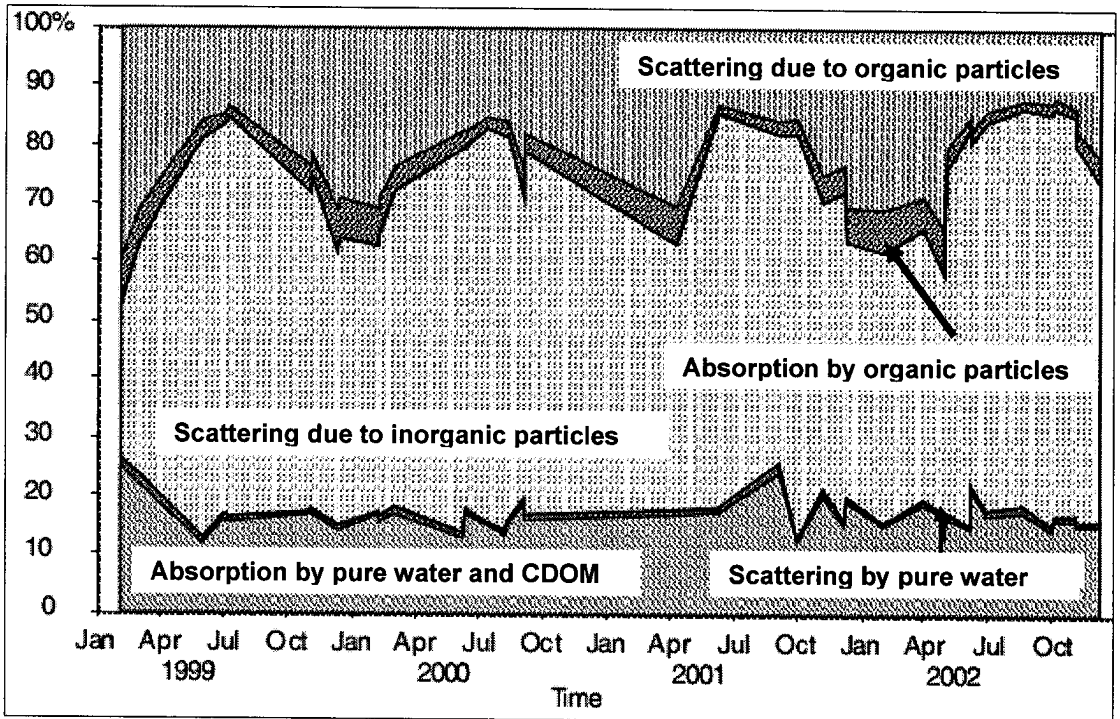

Figure 3-11. Results of an optical model showing the percentage of light absorption and scattering caused by water, CDOM (colored dissolved organic matter), and different types of particles, at different times of the year (modified from Swift et al. 2006). Inorganic particles refer to mineral or soil-based particles while organic particles include both living and dead matter.

Earlier investigations focused primarily on increased phytoplankton productivity and the onset of cultural eutrophication as the primary source of these particles (e.g., Goldman 1974, 1994). The long-term increase of primary productivity in Lake Tahoe has been attributed to increased nutrient loading acting in concert with the efficient recycling of nutrients (Goldman 1988). Mean settling velocities for nitrogen and phosphorus associated with particulate matter, as measured with large sediment traps deployed in Lake Tahoe (depths of 175, 290, and 400 meters), were 54 and 39 feet/year (16.4 and 12.0 meters/year), respectively (A.C. Heyvaert *In:* Reuter and Miller 2000). These correspond to settling times on the decadal scale. However, it is important to note that these represent net loss rates from the water column and are long and take nutrient recycling into account. With an average depth of over 984 feet (300 meters) and a maximum depth of over 1,640 feet (500 meters), many of the nutrients associated with particles are mineralized by bacteria and effectively recycled before settling to the bottom (Paerl 1973). Viewed in a different way, Heyvaert's values repesent the average residence time for nitrogen and phosphorus in the water column, and not the residence time of the particles with which they are associated.

The hypothesis that fine inorganic particles from soil and dust (<16 μm diameter) contribute to measurements of lake clarity loss was first published in 1999 (Jassby et al. 1999). This was immediately followed by the first comprehensive study of particle number, size and composition in Lake Tahoe during 1999-2000 (Coker 2000). Typical particle size distributions for over 40 samples from lake sampling stations are shown in Figure 3-9. It can be seen that the very fine particles dominate and that in the 10 – 16 µm range, particle numbers are almost negligible. The lower number of particles typically seen in the winter agrees with the observed higher Secchi depth readings during that season.

The original 1999-2000 investigation of particle size distribution has been followed up by a series of studies including the spatial and temporal distribution of particle concentration and composition in Lake Tahoe (Sunman 2001), characterization of biotic particles and limnetic aggregates in Lake Tahoe (Terpstra 2005), lake particles and optical modeling (Swift 2004, Swift et al. 2006) and distribution of fine particles in Lake Tahoe streams (Rabidoux 2005). Of the inorganic particles, the finer fraction (0.5 – 16 µm) has the greatest impact on light attenuation (Figure 3-10).

Particle loss to the bottom through sedimentation is an important parameter in any mass balance consideration of particle concentration in the water column. This was confirmed by Jassby (2006) who studied particle aggregation and developed a preliminary version of a particle loss model. Data from Sunman (2001) suggest that fine sediment particles (< 20 µm diameter) can be transported through the upper 329 feet (100 meters) of the water column in approximately three months. For clarification, there is a distinction between the estimated settling time of a few months for particles and the longer settling velocities for nitrogen and phosphorus as presented above. As noted, nutrients are mineralized from particulate organic matter and recycled as the settle in the water column. As a result there is a longer residence time for these nutrients in the water column. The transport of particles as reported by Sunman (above) refers only to the particle matrix itself and not the associated nutrients. Jassby (2006) modeled particle deposition for Lake Tahoe and found that particles aggregration increased the rate at which particles themselves settled.

Swift (2004) and Swift et al. (2006) developed an optical model for Lake Tahoe to link fine sediment particles and Secchi depth. The model takes into account algal concentration, suspended inorganic sediment concentration, particle size distribution and dissolved organic matter to predict Secchi depth and diffuse attenuation. Both biological (e.g., phytoplankton and detritus) and inorganic (terrestrial sediment) particulate matter are important contributors to clarity loss in Lake Tahoe (Figure 3-11). The high scattering cross-section of inorganic particles results in their often being the dominant cause of reduced light transmission, despite their numerical minority most of the year. This research suggested that currently (1999-2002) light scattering by inorganic particles contributed greater than 55 to 60 percent of total light attenuation; about 25 percent was due to organic particles; with the remaining 15 to 20 percent due to absorption by water and, to a much lesser extent, dissolved organic matter. Specifically for Lake Tahoe, these findings lend support to the earlier hypothesis (Jassby et al. 1999) that inorganic particles dominate clarity for most of the year, but that winter mixing of the deep chlorophyll layer results in greater attenuation by organic particles.

Coupling organic and inorganic particle concentrations in the lake to a predicted Secchi depth provides useful relationships that can be used to guide restoration efforts in the Tahoe basin. The Lake Clarity Model used for Lake Tahoe TMDL development is a combination of the optical model (results presented above), a hydrodynamic model customized for Lake Tahoe, an ecological model and particle fate models developed as part of the Lake Tahoe TMDL science plan (Perez-Losada 2001, Reuter and Roberts 2004, Sahoo et al. 2006). Chapter 6 focuses on the Lake Clarity Model and its initial results.

Lake Tahoe's annual average clarity can vary significantly from year-to-year based on nutrient and fine sediment loading (Jassby et al. 2003). For example, in the three years from 2000 through 2002 during lower total precipitation, lake Secchi depth increased by 3 meters. This level of Secchi depth change has been observed in the long-term data and suggests that lake response time to load reduction can be rapid. As reported by Heyvaert (1998), Lake Tahoe water quality was fully restored to historic conditions in about 20 to 25 years following the mass disturbance to the basin from the timber clear-cut activities in the late 1800's. As the basin was allowed to heal, lake condition improved (Figure 3-12). These findings suggest that nutrient and fine sediment reduction led to an increased water quality condition and consequently lake transparency, and in a relatively shorter time period than previously considered. Although the lake improved during this "Intervening Era" from 1901 to 1970, that historic recovery does not guarantee the current lake transparency conditions will be restored to the levels seen in the early 1970s.

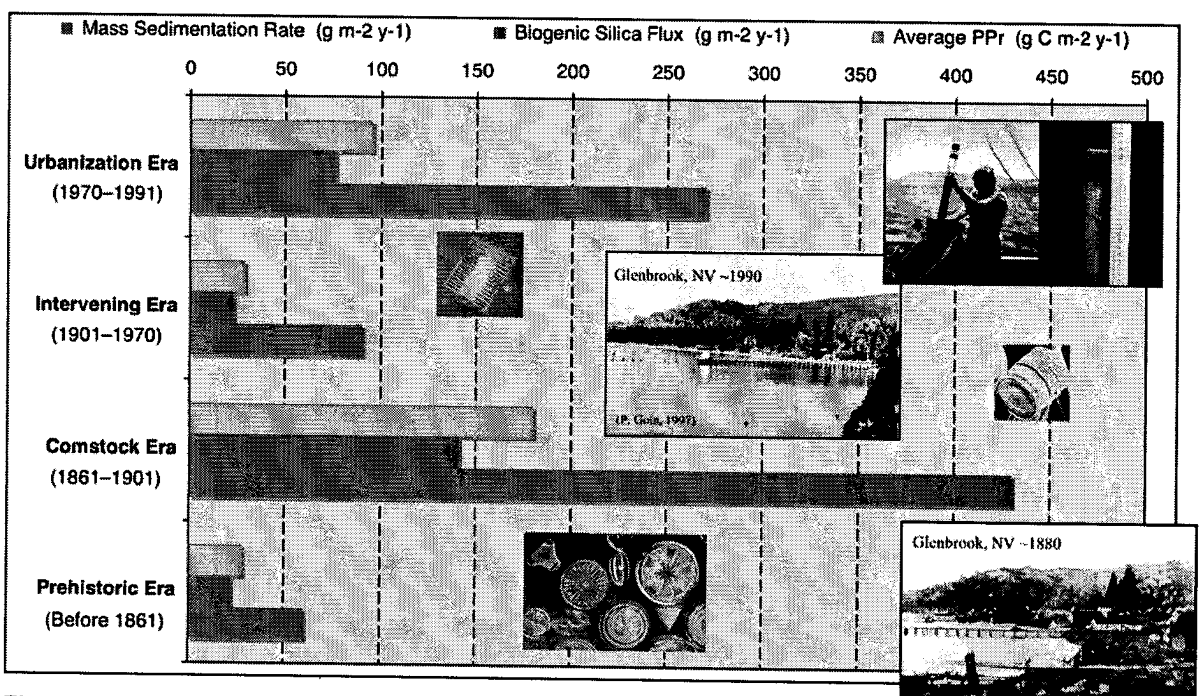

Figure 3-12. Summary of paleolimnologic studies that reconstruct the recent water quality history of Lake Tahoe. PPr indicates primary productivity (A.C. Heyvaert *In*: Tahoe Science Consortium 2007).

3.4.2 Water Quality in the Deep Water of Lake Tahoe

The deep water of the lake is referred to as the pelagic zone and is distinguished from the nearshore. The pelagic zone includes the lake's deep water column. In the pelagic zone sunlight penetrates through the uppermost part and the water column with the deeper portions in continual darkness. The vast majority of the lake's water is contained in the pelagic zone which acts a reservoir for nutrients and fine sediments that enter the lake. The continued loading of these pollutants over time has caused the decline in lake clarity and transparency. The lake's transparency is a function of the water's optical properties, and in addition to fine sediment particles, the lake's transparency is also affected by nutrient input and algal growth.

Nutrients

The nutrients that stimulate algal growth (primary productivity) in Lake Tahoe are nitrogen and phosphorus. However, the forms in which these nutrients are present have a large affect on how they are used by algae. This discussion will describe the forms of nitrogen and phosphorus, their bioavailability, and the concentration of these nutrient forms in the lake.

<u>Nutrient Forms and Bioavailability</u>

Algae require a nitrogen:phosphorus ratio of 7:1 (by weight). However, assessing nutrient limitation based on the concenrations of nitrogen and phosphorus in lake water and relating that to the 7:1 ratio is not necessarily accurate. According to Lewis and Wurtsbaugh (2008), the problem with using this stoichiometric approach (7:1) to evaluate nutrient limitation based on nitrogen and phosphorus water chemistry derives from uncertainty about the differential availability of nitrogen and phosphorus fractions in lake water.

The forms of nitrogen typically measured in lake water include nitrate (NO_3^-), ammonium (NH_4^+) and total Kjeldahl nitrogen (TKN). The organic nitrogen can be further divided into particulate and dissolved components. Dissolved organic nitrogen (DON) includes a wide array of chemical compounds, ranging from some of the more labile, or easily broken down, compounds, such as certain amino acids, to more refractory nitrogen-containing compounds that resist bacteria breakdown. Lake Tahoe is similar to most other lakes in that it also contains large portions of its total nitrogen pool as DON. Typically, nitrate and ammonium are directly available for algal uptake and growth. Organic nitrogen can be mineralized by bacteria to ammonium and some algae can use organic nitrogen directly as a source of nitrogen. Research in this area is generally limited. A study by Seitzinger et al. (2002) looking at nitrogen bioavailability in runoff from forest, pasture and urban land-uses in the northeastern United States found that 0 to 73 percent of the DON could be used by algae. Similarly, working in a montane stream, Kaushal and Lewis (2005) reported that use of DON by algae ranged from 15 to 73 percent. These are complex studies that have not been conducted at Lake Tahoe.

Phosphorus in lake water is typically defined by the method of analysis. While ortho-phosphate (PO_4^{-3}) is typically considered the form of phosphorus used by algal cells, measurements of phosphorus in water commonly include soluble reactive phosphorus (SRP), total dissolved phosphorus (TDP) and total phosphorus. SRP is the form of phosphorus that is considered mostly bioavailable. Part of the TDP includes SRP and part dissolved organic-phosphorus. Total phosphorus includes phosphorus from organic phosphorus as well as phosphorus associated with inorganic sediments. In a study conducted for the Lake Tahoe TMDL, Ferguson and Qualls (2005) found that about 20 percent of the total phosphorus associated with suspended sediment in selected Lake Tahoe tributaries was bioavailable and that about 35 percent of the total phosphorus in sediment from urban runoff was bioavailable. Ferguson and Qualls (2005) employed an approach where both chemical P-fractionation and algal bioassays were used to estimate BAP. In the bioassays, particulate P was trapped on a filter and separated by a member that allowed the passage of dissolved-P but not particulate P into the algal culture. Based on Ferguson and Qualls (2005) bioavailable phosphorus measurements and the distribution the various measured phosphorus forms in atmospheric deposition (Hackley et al. 2004), it was estimated that about 40 percent of the total phosphorus in atmospheric deposition was bioavailable. Dillion and Reid (1981) that found a range of 16 to 56 percent for the amount of bioavailable phosphorus in total phosphorus from atmospheric deposition in Canada. Ferguson and Qualls (2005) found the bioavailability of dissolved organic phosphorus in Lake Tahoe streams to be negligible.

Nutrient Concentrations in Lake Tahoe

The mean whole-lake concentration of total nitrogen for Lake Tahoe was calculated as 65 micrograms per liter (µg/L) from Jassby et al. (1995). Monitoring and research data summarized by Marjanovic (1989) indicate that particulate nitrogen comprises nearly 15 percent of total nitrogen, or in this case, 9 µg/L. The majority (85 percent) of total nitrogen occurs in the dissolved form either as DON or dissolved inorganic nitrogen (DIN). DIN consists of nitrate (15 µg/L) and ammonium (1 – 2 µg/L) and accounts for approximately 25 percent of total nitrogen. At a mean concentration of approximately 40 µg/L, DON constitutes the largest nitrogen fraction at 60 percent.

Mean, whole-lake total phosphorous concentration at the same time was 6.3 µg/L (Jassby et al. 1995). Particulate phosphorus, at a calculated concentration of 0.6 µg/L, was approximately 10 percent of the whole-lake total phosphorus. As was observed for nitrogen, most of the lake's phosphorus is in the dissolved form; TDP, at 5.7 µg/L. Further dividing TDP, SRP was 2.1 µg/L, and dissolved organic phosphorus (DOP) was 3.6 µg/L. Total acid-hydrolyzable-phosphorus (THP) represents that portion of total phosphorus (TP) converted to ortho-phosphorus following a relatively mild acid digestion during chemical analysis. THP is intended to represent the potentially bioavailable-phosphorus. The whole-lake average THP concentration was 2.6 µg/L and, as expected, the THP portion of TP is greater than particulate phosphorus (PP).

A comparison of the mean annual concentrations of nitrate and THP in the euphotic zone at the UC Davis - TERC deep water and index stations indicated that both locations were similar. The index station is positioned on the lake's western shelf, approximately two kilometers off-shore. For the period 1985 through 1993, nitrate at the index station was 4.9 ± 0.8 µg nitrogen/L and slightly higher than the average concentration of 4.5 ± 1.0 µg nitrogen/L at the deep water station (average of mean annual concentrations). The largest annual difference in nitrate between these two locations was in 1992, when nitrate at the index station was 3.6 µg nitrogen/L as compared to 2.8 µg/L at the deep water station. THP was virtually identical at these two stations, with the average of the mean annual concentrations equal to 2.9 µg/L for deep water and 3.0 µg/L for the index station.

Primary Productivity, Phytoplankton and Algal Growth Bioassays

The first measurements of phytoplankton (free floating algae) growth in Lake Tahoe were made in 1959 (Goldman 1974). At that time, the annual phytoplankton growth rate was slightly less than 40 g C $m^{-2}y^{-1}$ and typical of an ultra-oligotrophic lake. For the years prior to 1959, average annual primary productivity was reconstructed from an analysis of sediment cores. Heyvaert (1998) determined that the baseline, pre-disturbance (prior to 1861 and the Comstock logging period) primary productivity was 28 g C $m^{-2}y^{-1}$. Interestingly, the calculated value for 1900-1970, the period between the effects of the Comstock logging era in the late 1800's and the onset of urbanization of the Tahoe basin, was almost identical at 29 g C $m^{-2}y^{-1}$. This shows the ability of Lake Tahoe to return to historic levels following watershed recovery.

The rates of primary productivity recorded in 1959 were only about 30 percent more than the estimated baseline rates. Annual primary productivity of Lake Tahoe has increased by a factor of approximately five-fold since 1959 with a measurement of 203 g C $m^{-2}y^{-1}$ made in 2005 (Figure 3-13). Although there is year-to-year variation, the productivity data shows a highly significant upward trend that continues at a rate of approximately 5 percent per year. The largest single-year increases were found between 1982 and 1983 (28 g C $m^{-2}y^{-1}$ or 32 percent), 1988-1989 (30 g C $m^{-2}y^{-1}$ or 25 percent), 1992-1993 (33 g C $m^{-2}y^{-1}$ or 22 percent) and 1997-1998 (25 g C $m^{-2}y^{-1}$ or 15 percent). The magnitude of each of these large annual increases was similar to baseline productivity during the early part of the 20th century; highlighting the impact that nutrient loading has had on Lake Tahoe. These increases typically occur when complete lake mixing is accompanied by heavy precipitation and runoff.

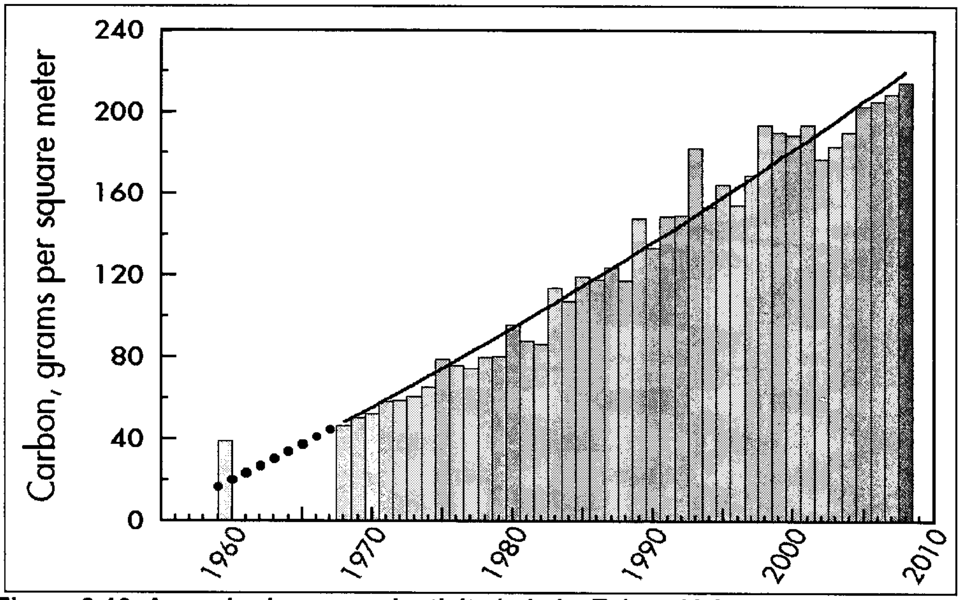

Figure 3-13. Annual primary productivity in Lake Tahoe. Values represent annual means from approximately 25 - 30 measurements per year (UC Davis - TERC 2009).

The long-term increase of primary productivity in Lake Tahoe is attributed to increased nutrient loading acting in concert with the lake's long hydraulic retention time (650 years) and efficient recycling of nutrients (Goldman 1988). With an average depth of over 984 feet (300 meters) and a maximum depth of over 1,640 feet (500 meters), many of the nutrient-bearing particles either remain suspended in the water column by lake mixing or the nutrients are mineralized by bacteria and effectively recycled before settling to the bottom (Paerl 1973). Year-to-year variability in primary productivity is directly related to the depth of mixing (Goldman et al. 1989).

Results from long-term algal growth response bioassay experiments show a clear shift from co-limitation by both nitrogen and phosphorus, to predominant phosphorus limitation (Goldman et al. 1993). This shift began in the early-mid 1980s, and has been explained by the accumulation of anthropogenic nitrogen from atmospheric deposition directly on to the lake surface (Jassby et al. 1994). Supporting evidence can be found in the phytoplankton species data. Atmospheric deposition provides most of the dissolved inorganic nitrogen (DIN) and total nitrogen in the annual nutrient load. Increased amounts of atmospheric nitrogen have caused an observed shift from co-limitation by nitrogen and phosphorus to persistent phosphorus limitation in the phytoplankton community (Jassby et al. 1994, 1995, and 2001).

The most recent algal growth bioassays (2002-2005) continue to show more frequent phosphorus stimulation relative to nitrogen stimulation (Hackley et al. 2005). When added individually, nitrogen was found to significantly increase algal biomass in 17 percent of experiments performed each year. In contrast, phosphorus stimulation caused an increase in algal biomass 57 percent of the time. Most importantly, when nitrogen and phosphorus are added in combination, algal growth was significantly higher in all of the experiments. Consequently, the control of both nitrogen and phosphorus is important.

The amount of free-floating algae (phytoplankton) in the water is determined by measuring the concentration of chlorophyll *a*. Though algae abundance varies annually, it does not show a long-term increase (Figure 3-14). The average annual chlorophyll *a* level in Lake Tahoe has remained relatively uniform at 0.6-0.7 µg/L since 1996.

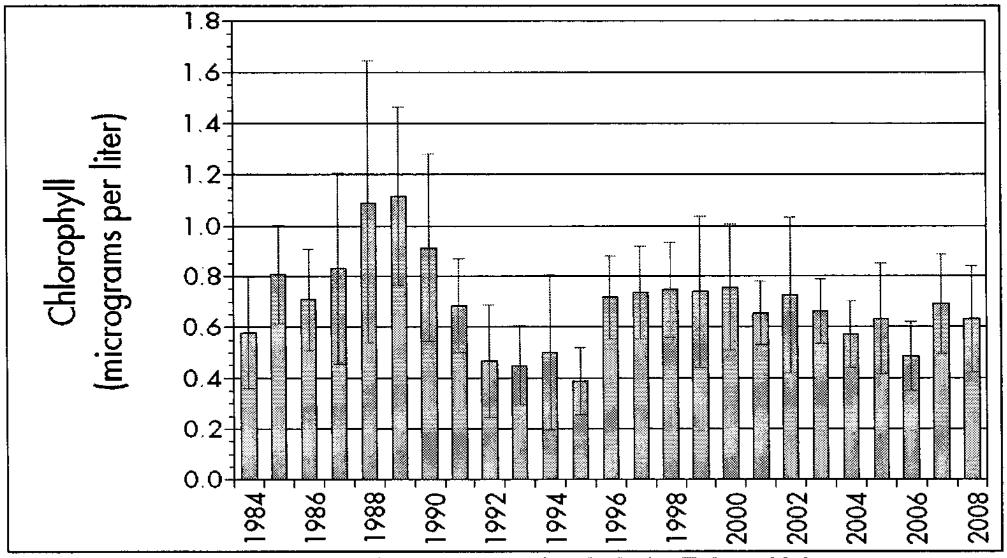

Figure 3-14. Annual chlorophyll a concentration in Lake Tahoe. Values represent annual means from approximately 25 - 30 measurements per year taken in the photic zone and volume averaged (UC Davis - TERC 2009).

Lake Tahoe has a deep-chlorophyll maximum, a common feature in the summer and early autumn, at a depth of 197 - 328 feet (60 - 100 meters) below the surface (Coon et al. 1987). While this biomass does not directly influence Secchi depth (20 - 30 meters deep), it was discussed above that these particles can affect transparency during the initial periods of lake mixing when they are swept up into the surface waters. Over the years the deep-chlorophyll maximum has risen in the water column to a shallower depth (Figure 3-15) (Goldman 1988, Swift 2004 UC Davis - TERC 2009).

Studies of phytoplankton species composition have helped to corroborate the shift in nutrient limitation and other changes in the lake. There is now a validated phytoplankton dataset that spans a 37-year period (the most recent data on phytoplankton distribution can be found in Hackley et al. 2005). Over the last four decades, changes have occurred in the standing crop, species composition and richness, and patterns of dominance (Hunter et al. 1990, Hunter 2004, UC Davis - TERC 2009). The overall decline in relative abundance of diatoms is indicative of Lake Tahoe's eutrophication, as is an observed increase in araphid pennate diatoms at the expense of centric diatoms. In addition, the disappearance of *Fragilaria crotonensis* after 1980 is attributed to its inability to compete well in phosphorus limited waters.

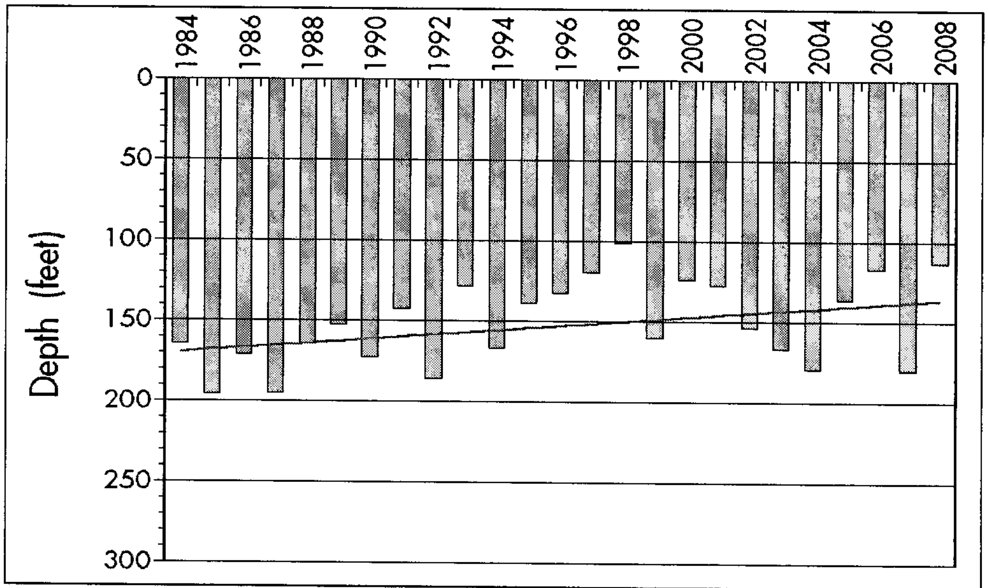

Figure 3-15. Long-term trend in the location of the deep chloroplyll maximum. Values are getting shallower over time, a trend believed to be associated with the decline in transparency (UC Davis – TERC 2009).

Deep Lake Mixing

Vertical stratification and mixing affect lake clarity. Stratification, or layering of waters, is created by layers of differing densities that impede top-to-bottom movement of water and pollutants. These density differences are primarily the result of varying temperature throughout the water column. Lake depth, size, shape, wind and other meteorological conditions also influence mixing and the stratification process. Stratification occurs during spring and summer due to heating by the sun. There are three layers in a stratified lake: (1) the epilimnion – a warm, lower density surface layer, (2) the metalimnion – a middle layer that contains the thermocline, which is the region where temperature changes most rapidly with depth, and (3) the hypolimnion – a cool, dense lower layer.

Thermal stratification in Lake Tahoe begins during the period February/March to April and reaches its maximum in August. The thermocline is strongest in late July/early September at a depth of approximately 66 feet (20 meters). As the summer progresses into fall, surface temperature is reduced and the thermocline weakens and deepens slowly until the winter when vertical mixing or turnover occurs. Deep mixing occurs when the water column is isothermal. Mixing or de-stratification generally occurs during autumn and winter, due to cooling air temperatures and wind (Pamlarsson and Schladow 2000). The depth of vertical mixing in Lake Tahoe varies from 328 feet (100 meters) to the bottom (approximately 500 meters), depending on the intensity of winter storms. On average, Lake Tahoe mixes to the bottom once every four years. This is a statistical average and mixing does not happen on a regular schedule (Figure 3-16).

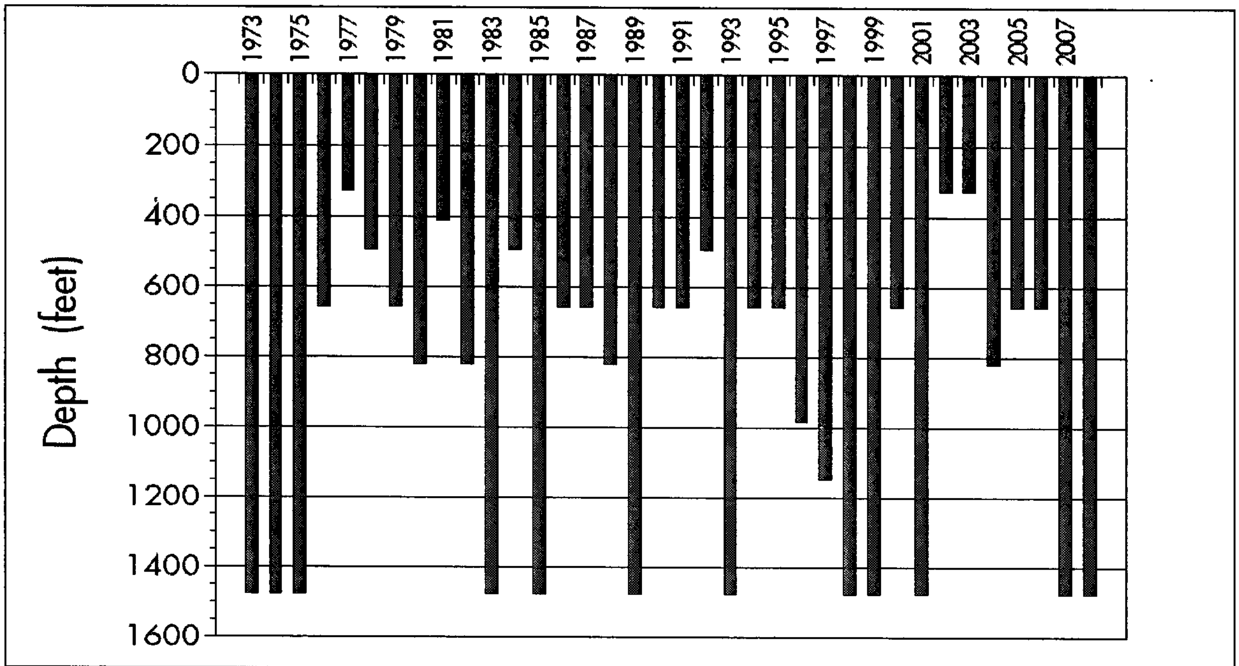

Figure 3-16. Historic time series for annual depth of mixing. The deepest mixing typically occurs in late February to early March, but Lake Tahoe does not mix completely to the bottom every year (UC Davis – TERC 2009).

Mixing is an important part of nutrient cycling and particle dynamics in Lake Tahoe. Mixing brings nutrient-rich waters from deeper portions of the lake to the epilimnion (surface) where, together with pollutants introduced by surface and subsurface runoff and atmospheric deposition, they can be utilized by algae and contribute to reduced lake transparency. There is a positive correlation showing that increased depth of mixing during the winter results in increased algal growth the following summer (Goldman and Jassby 1990a, b). Lake mixing and vertical circulation patterns also act to help position particles in the water column. The vertical distribution of these particles sets the conditions for clarity. Additionally, vertical circulation affects the settling rates for particles and limnetic aggregates. The UC Davis - TERC Lake Clarity Model includes a complete hydrodynamic sub-model to account for lake mixing and circulation processes on a 2-hour time scale.

Research and lake monitoring shows that significant vertical mixing can occur during summer months in addition to the annual mixing event (Pamlarsson and Schladow 2000). During sustained summer wind events, surface water can be forced downward and, in response, colder deeper water rises to the surface due to a process termed upwelling. During summer upwelling events, the Secchi depth often exceeds 30 meters due to the fact that deeper water lower in fine particle concentrations is brought to the surface.

Another important mixing process in Lake Tahoe occurs as streams discharge to the lake. Recent investigations have shown that water temperature, associated water density and stream flow have a profound impact on the depth at which influent stream water mixes in the lake (Perez-Losada and Schladow 2004). Because the influent streams carry significant sediment loads to Lake Tahoe, the insertion depth of the stream water has the potential to significantly affect lake clarity.

Since 1970, Lake Tahoe has warmed at an average rate of 0.015 °C per year (Figure 3-17) (Coats et al. 2006). This has increased the thermal stability and resistance to mixing of the lake, reduced the depth of the October thermocline and shifted the timing of stratification onset toward earlier dates. The warming trend is correlated with both the Pacific Decadal Oscillation and the Monthly El Nino-Southern Oscillation Index, but it results primarily from increasing air temperature and secondarily from increased downward long-wave radiation from the sun. The biological and water quality impacts of the changes in lake thermal structure have been the subject of discussion, but have yet to be documented in detail.

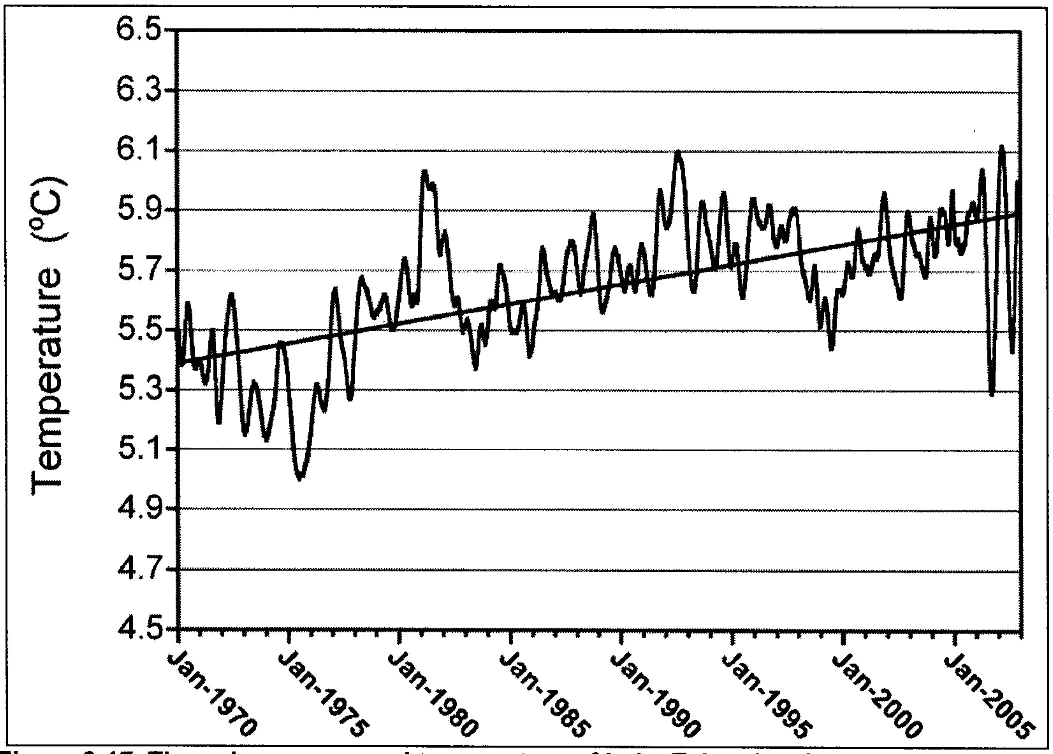

Figure 3-17. The volume-averaged temperature of Lake Tahoe has increased since 1970 (UC Davis - TERC 2009).

3.4.3 Nearshore Water Quality

This TMDL does not directly address restoring the nearshore clarity of Lake Tahoe. Rather, the Lake Tahoe TMDL focuses solely on restoring the deep water clarity and transparency. However, relevant research in the nearshore is summarized in this section to highlight the nature of the nearshore conditions. The nearshore is the area that connects the deep water to the upland and, though some research has been completed, the relationship between the lake's deep water clarity and the nearshore conditions is not well understood and additional research is planned to hopefully bridge that gap. Research on the lake's nearshore is presented in this Section to highlight some complexities and lack of understanding the relationship between the upland activities and the conditions in the nearshore.

For the purposes of the Lake Tahoe TMDL, the nearshore extends from the lake shoreline to about 66 feet (20 meters) of water depth, typically where the bottom can no longer be seen from above. The nearshore is the area of the lake where clarity is most obvious to the casual observer because the lake bottom can be seen. This TMDL-definition for the nearshore is different than the Tahoe Regional Planning Agency (TRPA) Code of Ordinances definition for "nearshore", which states, "the zone extending from the low water elevation of Lake Tahoe (6,223.0 feet Lake Tahoe Datum) to a lake bottom elevation of 6,193.0 feet Lake Tahoe Datum, but in any case, a minimum lateral distance of 350 feet measured from the shoreline."

The nearshore area is affected by surface loading either as direct discharge to the nearshore, tributary inflow, and groundwater loading. Water quality is historically measured in the nearshore as turbidity which is a measurement of water murkiness. Turbidity is expressed as nephelometric turbidity units (NTU) with higher values indicating less clarity, or greater murkiness (Taylor et al. 2003). Another indicator of nearshore water quality is the abundance and distribution of periphyton, or attached filamentous algae. Both of these nearshore indicators are discussed in this section.

Turbidity

A study by Taylor et al. (2003) explored nearshore clarity by collecting field measurements of turbidity between September 2001 and August 2003. Turbidity mesaurments made during this study are in Figure 3-18. It showed that California's nearshore numeric clarity objective for turbidity was exceeded in several areas. The study showed moderate to extremely elevated near-shore turbidity in the south shore area. Specifically, the mouth of the Upper Truckee River was characterized as having extremely elevated turbidity, while the Al Tahoe intervening zone, Bijou Creek, Tahoe Keys Marina and Ski Run Marina showed moderate levels of turbidity. These areas had maximum observed turbidities above 3 (NTU) or typical values near or above 1 NTU (i.e. above or near the numeric objectives).

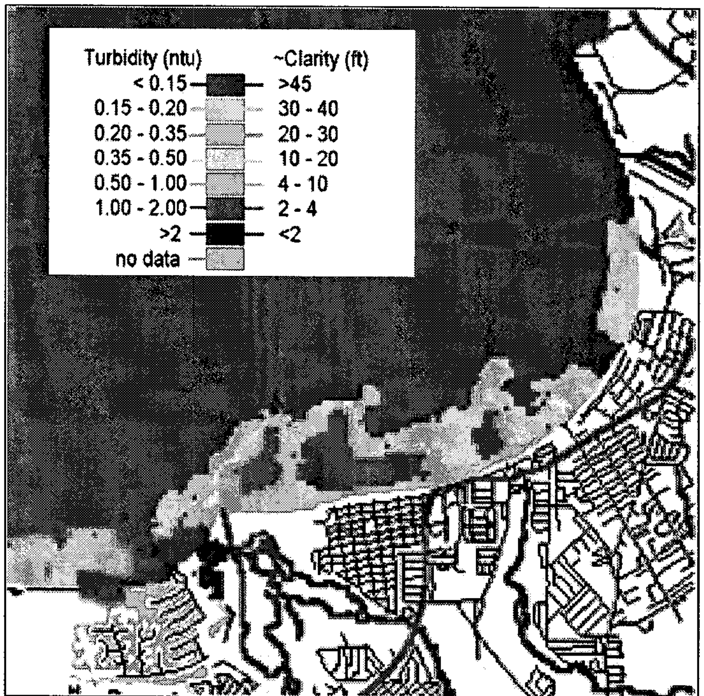

Figure 3-18. Measurements of nearshore turbidity along Lake Tahoe's South Shore on April19, 2003 following a lake level rain event (Taylor et al. 2003).

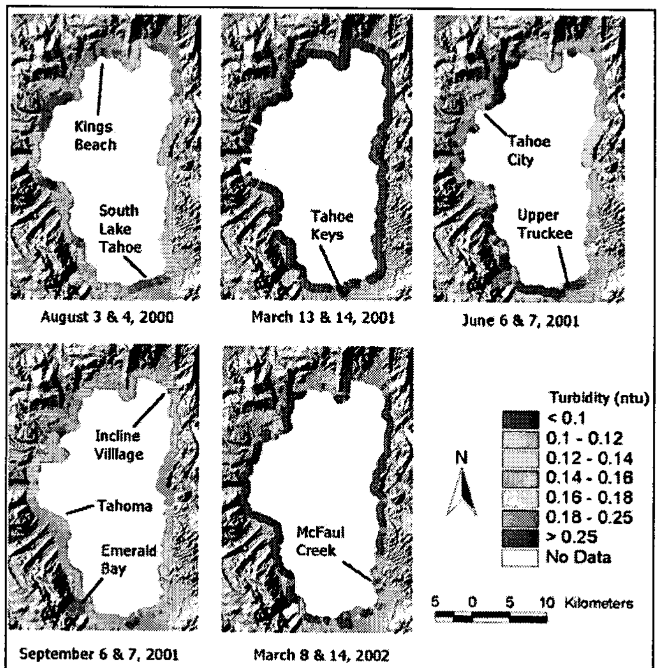

Figure 3-19. Synoptic monitoring of nearshore turbidity in Lake Tahoe showing seasonal and spatial variation (Taylor et al. 2003).

Approximately 0.93 miles (1.5 km) of the 71 miles (114 km) total shoreline (near the outlet of the Upper Truckee River) had extremely or moderately elevated turbidity. Extremely elevated turbidity was defined as a 123.5 acres (0.5 km^2) area with typical turbidity above 0.5 NTU and maximum turbidity above 2.5 NTU. Moderately elevated turbidity was defined as a 123.5 acres (0.5 km^2) area with typical turbidity above 0.35 NTU and maximum turbidity above 1.5 NTU. Four km of the total shoreline (further east on the south shore to the vicinities of Bijou Creek and Ski Run Marina, and near Tahoe Keys) had moderately elevated turbidity and 5.6 miles (9 km) further east had slightly elevated turbidity. The highest measurements coincided with spring snowmelt and runoff, and also had the highest ratios of mineral to algal particle content. Summer thunderstorms had a lesser but still discernable effect on nearshore clarity. Figure 3-19 provides a synoptic view of nearshore turbidity. Areas associated with chronically elevated turbidity occur most frequently in proximity to urbanized areas during periods of surface water discharge.

Attached Algae

Some of the first visible evidence of eutrophication of Lake Tahoe was the increased amount of attached algae or periphyton growth along the shoreline in the 1960s. The accumulation of attached algae on rocks, piers, boats and other hard-bottomed substrates is a striking indicator of Lake Tahoe's declining water quality for the largely shore-bound population. Thick, green or white expanses of periphyton biomass often coat the shoreline in portions of the lake during the spring. When this material dies and breaks free, beaches can be littered with mats of algae. The nearshore periphyton can significantly impact the aesthetic beneficial use of the shorezone.

Under the current periphyton monitoring program, collections are made at 10 stations (five each in California and Nevada), nine of which have historical data on periphyton biomass. Samples of natural periphyton are collected directly from rocks at 1.6 feet (0.5 meter) depths, approximately monthly during the peak growth season (January-June) and less frequently during the remainder of the year (July-December). The units of biomass are chlorophyll *a* per square meter of lake bottom area (Hackley et al. 2004, 2005).

Measures of annual maximum, average annual and baseline chlorophyll *a* were determined for 2000-2003 and these values were compared with historical data collected from 1982-1985 (Figure 3-20). The average annual maximum biomass measured as chlorophyll *a* concentration was clearly higher in areas of high development in the northwest portion of the lake during both periods. In contrast, the average maximum biomass was consistently lower at undeveloped east shore sampling locations.

Attached algae also exhibit a distinct seasonal pattern (Figure 3-21) of high biomass accrual in the spring and early summer, followed by a die-off and sloughing of biomass in mid-summer. Periphyton biomass returns to near its annual baseline level by July. Periphyton growth is stimulated by the elevated nitrogen and phosphorus loading associated with the spring surface runoff and groundwater flow (Loeb 1986, Reuter and Miller 2000).

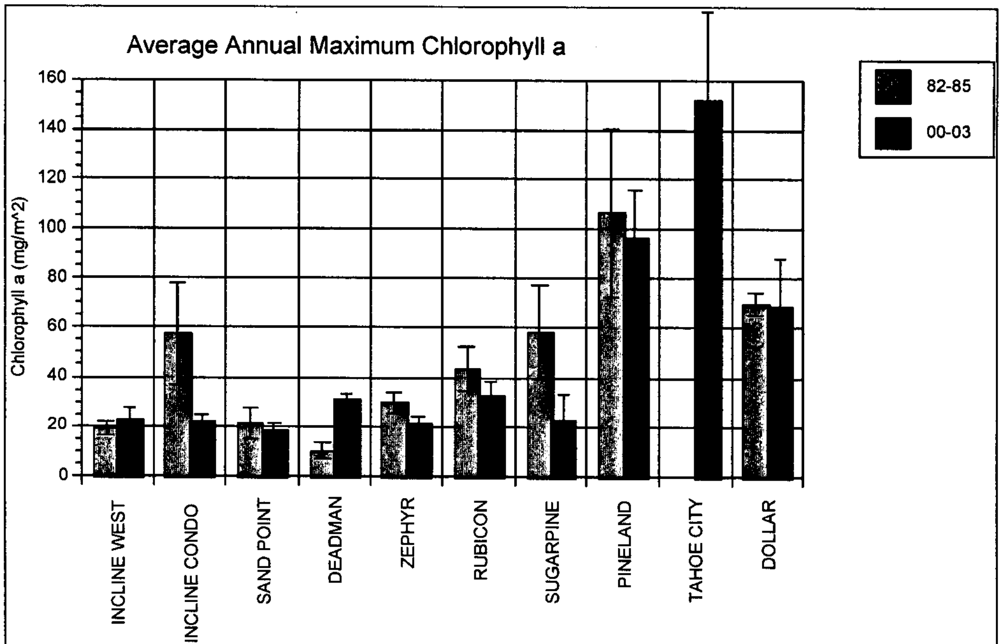

Figure 3-20. Synoptic distribution of attached algae at 10 monitoring sites in Lake Tahoe (Hackley et al. 2004).

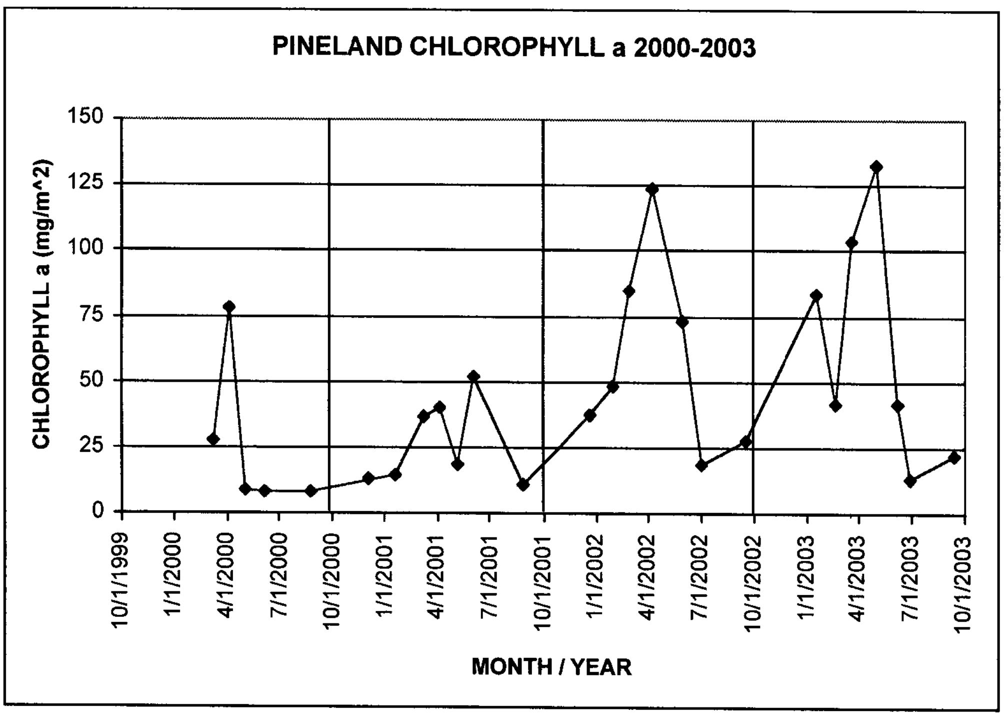

Figure 3-21. Seasonal distribution of attached algae from a depth of 0.5 meter at the Pineland sampling site located on the west shore in the vicinity of Ward Creek (Hackley et al. 2004).

4 Source Analysis

Significant research on pollutant sources has been completed as part of the Lake Tahoe TMDL development. This research has greatly improved our understanding of individual pollutant sources, distribution of sources, magnitude of pollutant load, and specific pollutant species. This section of the report provides detailed summaries of work done to better understand and evaluate sources of pollutants to Lake Tahoe. This work was specifically designed to build on the research, data, and information available in the Tahoe basin.

Pollutant source information in the Tahoe basin has typically focused on individual site evaluations or specific sources within a subwatershed. A notable exception is the Watershed Assessment (USDA 2000) and Reuter et al. (2003) which identified major source categories of pollutants, including:

- Stream loading (from tributaries)
- Intervening zones (areas that discharge directly into the lake)
- Atmospheric deposition
- Groundwater
- Shoreline erosion

As of 1968, all of Lake Tahoe's treated sewage effluent was pumped out of the basin; a management practice that continues to this day. Consequently, this source is not relevant with respect to this TMDL.

Using information available at the time, Reuter et al. (2003) developed the first nutrient budget for Lake Tahoe in 1998 (Table 4-1). The budget focused on nitrogen and phosphorus as it was thought that phytoplankton were the principal cause of clarity loss. It wasn't until 1999 (Jassby et al. 1999) that serious concern was raised about the impact of fine sediment particles on lake transparency.

Table 4-1. Pollutant loading estimates for Lake Tahoe (metric tons per year) as revised in 2000 (Reuter et al. 2003).

Source Categories		Total Nitrogen	Total Phosphorus
Upland Runoff	Stream Loading	82 (20%)	13.3 (31%)
	Intervening Zones	23 (5%)	12.3 (28%)
Atmospheric Deposition		234 (59%)	12.4 (28%)
Groundwater		60 (15%)	4 (9%)
Shoreline Erosion		1 (1%)	1.6 (4%)
TOTAL		400	43.6

Initial results from modeling the optical properties of water in Lake Tahoe highlighted the significant impact that fine particles have on clarity and transparency. It is estimated that approximately 60-70 percent of clarity loss is the result of fine particle interaction with light and water (Swift et al. 2006). Consequently, estimating the contribution of fine sediment from identified sources was a significant effort associated with the Lake Tahoe TMDL related research. Additionally, research focused on providing information on the specific forms of pollutants from each source, and to the extent possible, additional refinement to the major source categories. Stream channel erosion was identified and evaluated as a source of pollutants. Table 4-2 lists the source areas evaluated in this document to develop an updated pollutant budget for Lake Tahoe.

Table 4-2. Listing of pollutant sources evaluated as part of the Source Assessment.

Urban Areas	Single Family Residential
	Multi-family Residential
	Primary Roads
	Secondary Roads
	Commercial/Institutional/ Communications/Utilities
	Turf Areas
Forest Areas	Unpaved Roads
	Ski Areas
	Recreational Areas
	Burned Areas
	Timber Harvest Areas
	Five Different Erosion Potential Areas
Groundwater	South Lake Tahoe/Stateline
	Tahoe City/West Shore
	Tahoe Vista/Kings Beach
	Incline Village
	East Shore
Stream Channel Erosion	Stream Channel Loading Estimates for all 63 Tributaries
Atmospheric Deposition	
Shoreline Erosion	

The urban areas identified in Table 4-2 also include loading estimates from pervious and impervious surfaces areas. Estimates of fine sediment loading and fine sediment particle counts were also developed for each source category. Each source evaluation used Tahoe specific data and information. When literature values were applied, similar climates and settings were selected. In most instances, new data was collected in the Tahoe basin as part of the evaluations.

The source loading estimates were applied to the Lake Clarity Model for evaluating the lake's response to the pollutant loading conditions. The urban and forest upland loading estimates were developed for the Lake Tahoe Watershed Model with the use of the Loading Simulation Program C++ (LSPC). The stream channel loading estimates were also applied to the Lake Tahoe Watershed Model to better represent stream channel loading. This allowed for the development of individual estimates of in-channel and upland pollutant sources. These combined estimates were then used as input to the Lake Clarity Model, while pollutant loading estimates from groundwater, atmospheric deposition, and shoreline erosion were used as direct inputs to the Lake Clarity Model.

Table 4-3 provides the updated pollutant loading estimates for Lake Tahoe.

Table 4-3. Updated Pollutant loading estimates based upon work completed as part of the Lake Tahoe TMDL development.

Source Category		Total Nitrogen (metric tons/year)	Total Phosphorus (metric tons/year)	Number of Fine Sediment Particles ($x10^{18}$)
Upland	Urban	63	18	348
	Non-Urban	62	12	41
Atmospheric Deposition	(wet + dry)	218	7	75
Stream Channel Erosion		2	<1	17
Groundwater		50	7	NA**
Shoreline Erosion		2	2	1
TOTAL		397	46	481

**NA=Not Applicable since it was assumed that groundwater does not transport fine sediment particles.

Numerous projects were funded as part of the Lake Tahoe TMDL and were intended for direct use in this Technical Report. In some cases, the language from portions of those project reports was directly used in this document with minor editing. In particular, the following studies were conducted in direct support of the Lake Tahoe TMDL, and portions of their reports are incorporated into the text of this Technical Report.

Groundwater

USACE (United States Army Corps of Engineers). 2003. *Lake Tahoe Basin Framework Study: Groundwater Evaluation*. U.S. Army Corps of Engineers, Sacramento District.

Stream Channel

Simon, A., E.J. Langendoen, R.L. Bingner, R. Wells, A. Heins, N. Jokay and I. Jaramillo. 2003. *Lake Tahoe Basin Framework Implementation Study: Sediment Loadings and Channel Erosion*. USDA-ARS National Sedimentation Laboratory Research Report. No. 39.

Simon, A. 2006. *Estimates of Fine-Sediment Loadings to Lake Tahoe from Channel and Watershed Sources*. USDA-Agricultural Research Service, National Sedimentation Laboratory. Oxford, MS.

Atmospheric

CARB (California Air Resources Board). 2006. *Lake Tahoe Atmospheric Deposition Study (LTADS)*. Final Report – August 2006. Atmospheric Processes Research Section, California EPA, Sacramento, CA.

Upland
Tetra Tech, Inc. 2007. *Watershed Hydrologic Modeling and Sediment and Nutrient Loading Estimation for the Lake Tahoe Total Maximum Daily Load.* Final modeling report. Prepared for the Lahontan RWQCB and University of California, Davis.

Shoreline Erosion
Adams, K.D. and T.B. Minor. 2001. *Historic Shoreline Change at Lake Tahoe from 1938 to 1998: Implications for Water Clarity.* Desert Research Institute, Reno, NV. Prepared for the Tahoe Regional Planning Agency.

Adams, K.D. 2004. *Shorezone Erosion at Lake Tahoe: Historical Aspects, Processes, and Stochastic Modeling.* Desert Research Institute, Reno, NV. Prepared for the Tahoe Regional Planning Agency.

Each of these reports reviewed available information and, in most cases, built upon research previously conducted on more limited scales. For additional detail and description of research conducted on each source category, each of the above reports should be referenced individually. The content of these reports was largely summarized in this document with enough detail included to allow the reader to fully understand the methods, scope, and detail of research conducted for each source category. For areas where new information was not collected, the most recent and comprehensive analyses were used.

Figure 4-1, Figure 4-2, and Figure 4-3 are pie charts of the relative pollutant loading from each source category. The loading values presented in this report are based on data collected largely since 2000 and reflect relatively recent development and land-use conditions. Note the urban upland sources are estimated to contribute close to three fourths of all the fine sediment particles to Lake Tahoe. This information highlights the significance of urban uplands as a primary pollutant source of fine sediment.

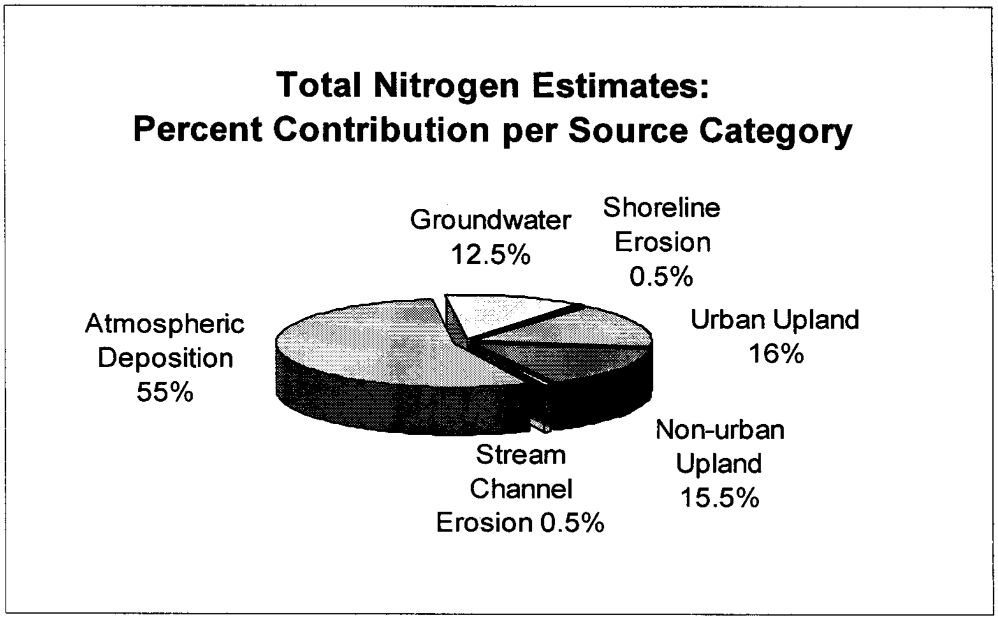

Figure 4-1. Relative Nitrogen Mass Loading by Source Category.

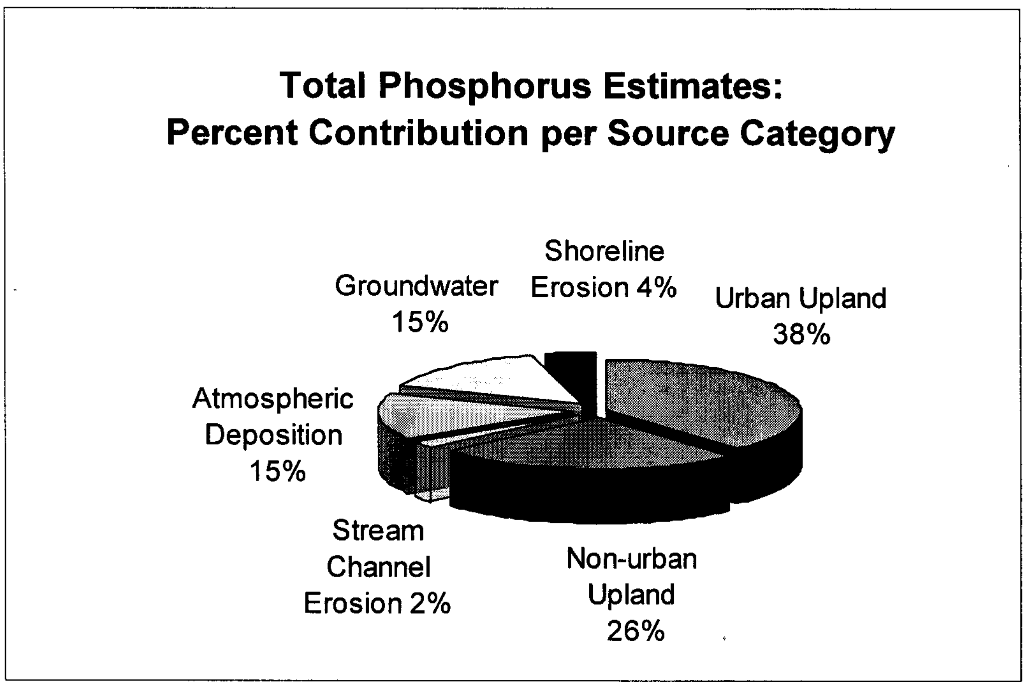

Figure 4-2. Relative Phosphorus Mass Loading by Source Category.

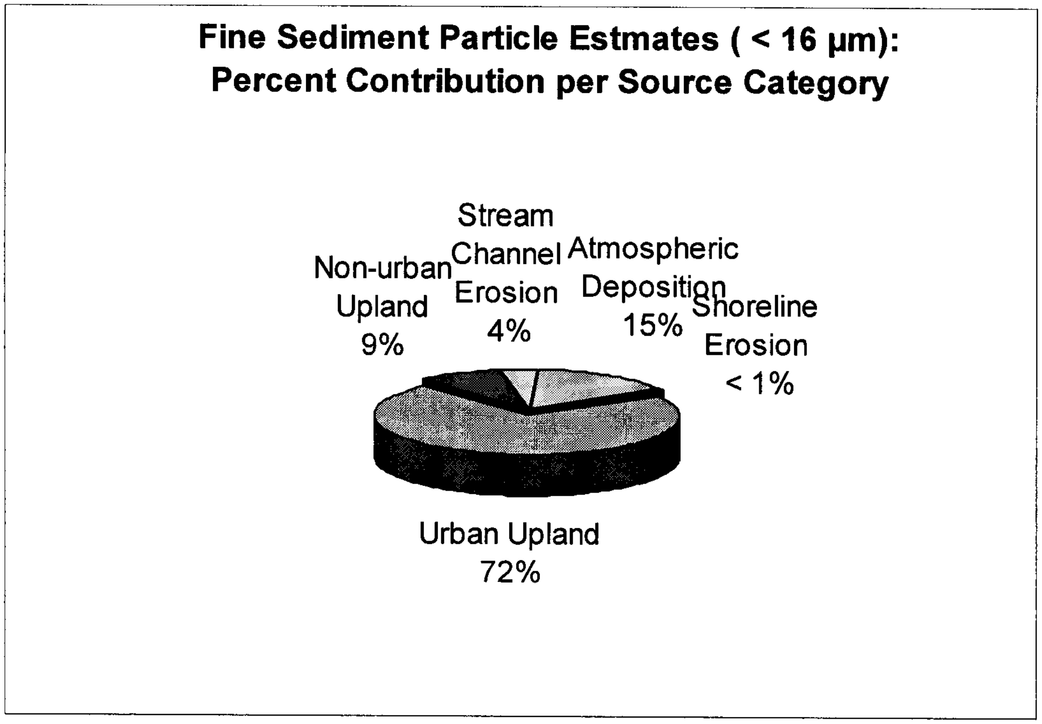

Figure 4-3. Relative Fine Sediment Particle Loading by Source Category.